THE DEVELOPMENT OF

A CONCENTRATING SOLAR TRAP

by

RICHARD WILLIAM ELLIOTT

The research carried out and submitted here for the degree of Master of Philosophy has been carried out by Richard William Elliott.

Director of Studies: G. T. Roberts

Candidate: R.W. Elliott

September 1987

DECLARATION

I hereby declare that this research has not been accepted or currently being submitted for any degree other than the degree of Master of Philosophy of the Council for National Academic Awards.

R.W. Elliott

R.W.ELLIOTT

September 1987

THE DEVELOPMENT OF

A CONCENTRATING SOLAR TRAP

by

RICHARD WILLIAM ELLIOTT

A thesis submitted during the Summer 1987 in partial fulfilment of the award of M.Phil. by the C.N.A.A. describing the research carried out at the sponsoring establishment: The Polytechnic of Wales.

Work carried out in collaboration with University College Cardiff.

ACKNOWLEDGEMENTS

My thanks to Dr. G.T. Roberts for his patience, advice and use of testing facilities.

I would also like to thank both Mr. N. Morris and Mr. B. Minty for their technical skills and assistance.

THE DEVELOPMENT OF

A CONCENTRATING SOLAR TRAP

by

RICHARD WILLIAM ELLIOTT

ABSTRACT

Even though most variations of solar collector have been tried and tested at some stage or other an important family of concentrating solar trap has been overlooked. This class of collector has combined together the advantages of some of the other collector types by overcoming their individual disadvantages. A concentrating solar trap acts like a non-focussing radiation funnel which by refraction and reflection concentrates solar energy. This thesis demonstrates that for moderate concentrations this collector geometry has better optical efficiencies and acceptance angles than other known concentrators. The investigation has carried out an optimisation simulation aimed at providing the best possible collector geometry without diurnal tracking for a concentrating solar trap using a super-viscous liquid with a high transmittance coefficient and low thermal conductivity. The resulting computer simulation predicted very favourable results for these physical conditions. An experimental collector was built and tested and a comparison of the computational and experimental results for efficiency under steady state conditions has been carried out which confirms the correctness of the simulation. However until such time as a suitable trap material becomes available this collector is not thought to be commercially viable. However the mechanism for predicting the best collector geometry for any trap transmittance has been developed here and can be used with confidence.

CONTENTS

		Page No.
CHAPTER 1.	INTRODUCTION.	
1.1	The nature of solar radiation.	1
1.2	Types of collectors.	2
1.3	The proposed concentrating solar trap.	12
1.4	The development of a concentrating solar trap.	15
1.5	Comparisons and conclusions.	19
CHAPTER 2.	OPTIMISING COLLECTOR EFFICIENCY.	
2.1	Introduction.	21
2.2	The collector shape specification.	23
2.3	The optical efficiency simulation design.	46
2.4	Optimum collector shape choice.	51
2.5	Experimental ray tracking verification.	55
CHAPTER 3.	SIMULATION OF HEAT TRANSFER AND TEMPERATURE DISTRIBUTION.	
3.1	Introduction.	66
3.2	The steady state finite difference heat transfer model.	69
3.3	The heat generation simulation.	72
3.4	The thermal resistance simulation.	86
3.5	The steady state collector temperature and energy system.	95
3.6	The unsteady heat transfer model.	109
3.7	The thermal capacity simulation.	112
3.8	The collector temperature versus time simulation.	117
CHAPTER 4.	COLLECTOR DESIGN AND CONSTRUCTION.	
4.1	Introduction.	129
4.2	The physical requirements of the collector.	133
4.3	The physical properties of the materials.	138
4.4	Experimental measurement of solar transmittance through Hyvis.	147
4.5	The practical construction of the collector	153
CHAPTER 5.	EXPERIMENTAL PROCEDURE AND RESULTS.	
5.1	Introduction.	159
5.2	An Outline of the experimental procedure.	160
5.3	The experimental measurements.	163
5.4	The experimental recording.	166
5.5	The experimental results.	168
CHAPTER 6.	CONCLUSION AND FUTURE DEVELOPMENTS.	
6.1	Introduction.	184
6.2	Conclusions of the optical efficiency.	184
6.3	A comparison of the simulated and experimental results.	185
6.4	A comparison with other collectors.	188
6.5	Implications and improvements of the collector.	190

THE DEVELOPMENT OF A CONCENTRATING SOLAR TRAP

CHAPTER 1

INTRODUCTION

1.1 THE NATURE OF SOLAR RADIATION

It has been the ambition of many eminent scientists to construct a device that could use the energy radiated by the sun to perform some useful function, such as heating or producing electricity. Their endeavours over the past fo rty years has produced a diversity of energy collection and transfer systems. However before we consider the work which has been carried out in this field up to the present day it is worthwhile evaluating what properties are exhibited by solar radiation.

The sun has an effective temperature of approximately $5762^{o}K$ and at best the insolation at the earth's surface is approximately 1KW m^{-2} normal to its direction with the majority of the energy distribution in the wavelength band from 0.3 - 3.0 um and centred about a wavelength of 0.5 um. The effect of the atmosphere on the insolation causes scattering and absorption of energy at certain wavelengths caused mainly by water vapour, water droplets, carbon dioxide, aerosols and dust. This has the effect of reducing the solar energy constant of 1353 Wm^{-2} outside the atmosphere to a value depending on weather conditions but rarely reaching 956 Wm^{2} at sea level. Radiation that is not scattered is called beam or direct radiation whereas scattered radiation which varies from 10% on a clear day to 100% when cloudy is called diffuse radiation. Solar radiation therfore suffers from low intensity, intermittency and even total availability, but nevertheless once a method of its collection has been devised it will give an endless energy supply. The underlying aim of all solar collector designs is to acheive this energy collection as cost effectively as possible, this often becomes somewhat confusing when included with other parameters such as working conditions.

Infact in general we find that the best choice of collector will vary depending on the use to which it is going to be put and the climatic conditions under which it has to operate. The criteria of high efficiency, simplicity and economy for assessing a collector, first put forward by Telkes in 1949, are the aims of solar collector designers. Many improvements have taken place over the intermittant years with the success or failure of each depending on the need for all energy saving devices to be cost effective.

However in order to present a coherent and meaningful introduction to this topic it is necessary at this point to confine the scope of our interest to the types of collector used for supplimentary domestic energy supplies. There are basically three types of solar collector, used for this purpose of water heating which are, flat plate collectors, moderately concentrating collectors and evacuated collectors, each of which has its own distinct operating characteristics.

1.2 TYPES OF COLLECTORS

1.2.1 FLAT PLATE AND GLAZED COVER SYSTEMS

The simplest flat plate collector's normally use a receiver surface incorporating a device for removing heat from the plate. These are very simple and cheap to construct but only operate well at near ambient temperatures because of their high thermal losses. However they are very successful for heating such things as swimming pools where very often the water temperature is below the ambient temperature.

In order to try and prevent heat losses from a collector absorber {ref.1.1} it has been found beneficial in some circumstances to place a cover over the top of the collector. This has the effect of suppressing the heat loss from the absorber but also unfortuneately reduces the amount of energy reaching the absorber in the first instance.

Covers are therefore only beneficial to the system where the required output temperature is above the ambient temperature and the number of covers required to optimise the efficiency of the collector will depend on how much the output temperature is elevated above the ambient. The cover system cuts down heat losses in two different ways, by suppressing convection currents above the receiver and by being partially opaque to thermal radiation emmitted by it as well. The optimisation of the number of covers is a careful balence between lost incident energy and increased cost against required operating conditions. In general these collectors are most useful for low grade heating with no particular benefit in having more than a maximum of two covers.

Any attempt to limit the heat loss from this type of collector is very difficult because of the actual area of the absorber. Energy being lost by convection and radiation from the top and by conduction through the insulated back of the collector. An increase in the insulation thickness will reduce the loss but must be considered against other factors such as operating conditions and whether or not it would produce actual savings.

An advantage of flat plate collectors over some other types is that it does not suffer from shading, for it can be tilted to any angle to maximise the incident radiation intensity and does not suffer from 'end effects', the depth to aperture ratio being very small.

By far the most effective method of reducing heat loss that has taken place in this field has been the introduction of selective surfaces. These are surfaces that exhibit high absorption to solar radiation and yet are reluctant thermal radiators. This has the effect of reducing radiation losses from the collector and has greatly improved the efficiencies of both flat plate and evacuated systems. The first commercial processes were pioneered by Tabor in 1964 and since then several investigations and improvements have taken place. Black chrome being one of the best having an absorptance to emmissivity ratio of 10.86.

1.2.2 EVACUATED SYSTEMS

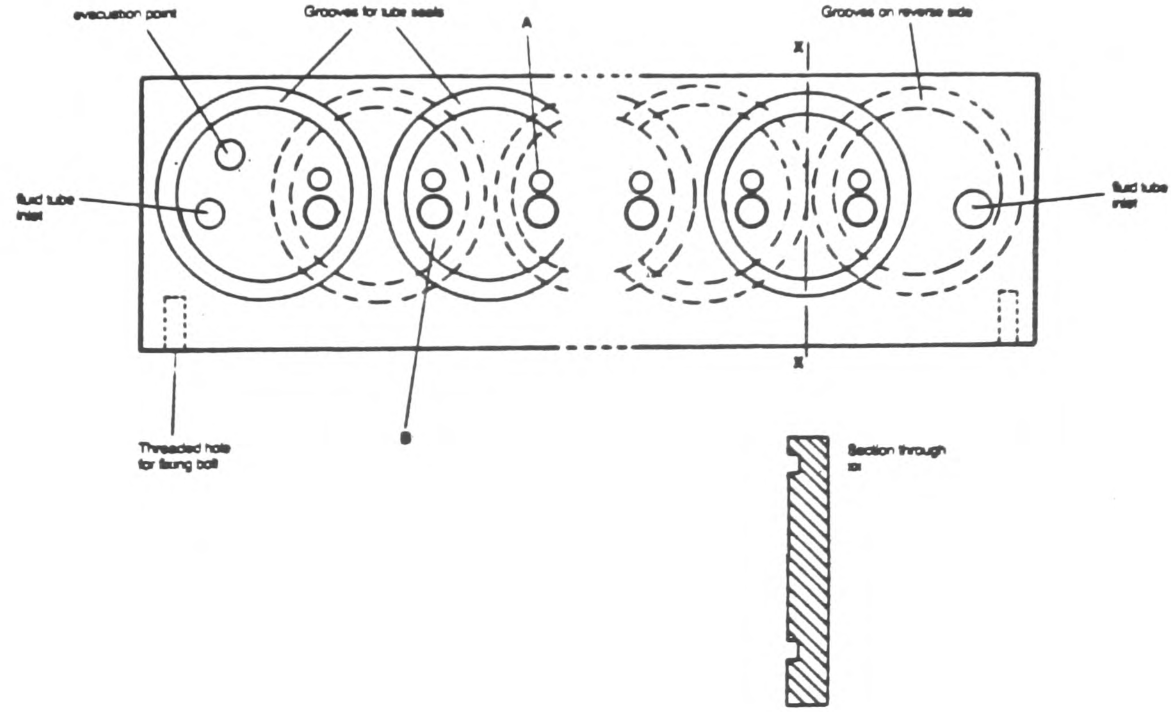
In order to eliminate convection and conduction losses the atmospheric pressure of the space surrounding the receiver is reduced to below 10^{-3} Torr {ref.1.2}, at which these losses become negligible. Due to the low pressures involved most of this type of collector are placed inside glass tubes which are capable of withstanding the pressures involved. Evacuated collector systems, as shown in Fig.1.1, fall into two categories those with high vacuum, with pressures less than 10^{-4} Torr, and those with partial vacuums {ref.1.3} using pressures in the range of $\simeq$ 15 Torr but use low thermal conductivity gas to suppress conduction. All of these collectors use a selective surface absorber to minimise radiation losses.

Of all the types of systems available these are the most efficient and perform equally well for all working conditions due to low heat loss. The main disadvantage of this type of collector is that they are also the most expensive, especially the Philips and Owens-Illinois high vacuum systems which need expensive metal to glass manifolds to seal the tubes. A recent cost effective comparison of commercially available collectors has shown that the Roberts Partially Evacuated System {ref.1.2} has good commercial potential and is currently undergoing manufacturing and production development.

1.2.3 MODERATELY CONCENTRATING SOLAR COLLECTORS

The heat loss from a receiving surface can be reduced by concentrating the solar radiation onto a smaller absorbing area. The magnification of the system being defined as the ratio of the aper ture area to that of the receiver area. The effect on the heat loss is considerable because conduction, convection and radiation all depend on the receiver area. This concentration also has the effect of increasing the operating temperature of a collector since reduced receiver area normally implies a reduced thermal mass. The viability of this type of collector therefore depends on the extra cost involved in producing the optical geometry and the reflectivity of the material used.

THE ROBERT'S PARTIALLY EVACUATED SOLAR COLLECTOR



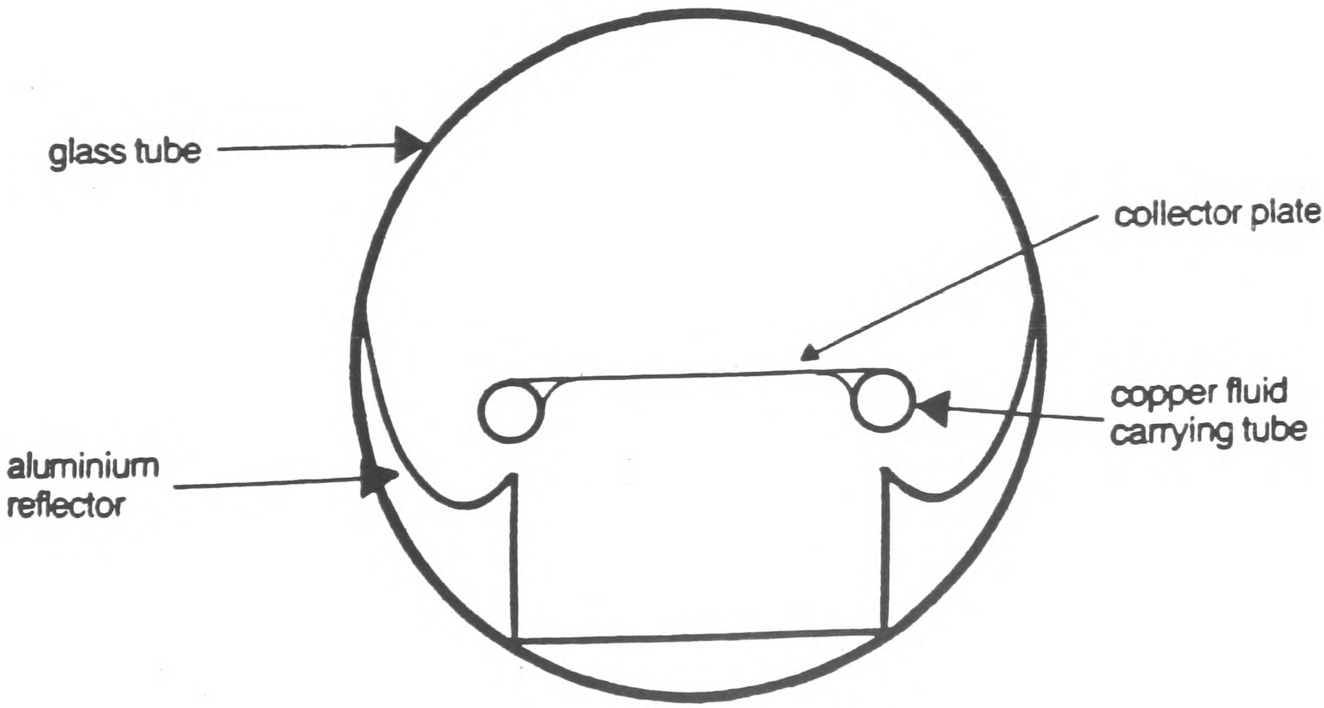


Fig. 1.1

Several different designs have been investigated over the past twenty years, the most common being Compound Parabolic Collectors (CPC's) and 'V' trough Collectors. The CPC as shown in Fig.1.2 was first described by Winston in 1974 {ref.1.4} since then many investigations into their limitations {ref.1.5} and truncation {ref.1.6} have been carried out. The title of 'ideal' had been bestowed on this type of collector because it is capable of achieving the highest possible concentration ratio for a given acceptance angle and absorber geometry {ref.1.7}. However although this is an attribute of the collector it does have some disadvantages which should be highlighted. For instance, the small acceptance angles of the collector above which no radiation can reach the receiver restricts its use to a tracking device or alternatively the magnification has to be reduced.

Also, inherent with this type of collector is that for reflections close to the receiver the incident angles of the solar beam on the receiver are very large causing a high proportion of the incident energy to be reflected. This alone can reduce the effective absorptance of the incident energy by $\simeq$ 25% for incident radiation near the acceptance half angle. Another effect of focussing is the presence of hot spots or uneven intensity on the absorbing surface. For some applications defocussing has been carried out to overcome this problem.

To try and reduce the cost of the mirrored surfaces of the collector investigations into reducing the mirror area by truncation have been undertaken. Reports have shown that this increases the acceptance angle and decreases the number of reflections, but also increases thermal losses. This then implies that there is an optimum degree of truncation that can be carried out. Truncation also has the advantage of reducing 'end effects' {ref.1.8} because of the reduced collector height, this can significantly increase collector efficiency especially where the cylindrical length of the collector is less than a metre. Most collectors of this type are designed with half angle acceptances of 30^{o} giving a concentration of 2 and mounted in an East-west direction with a tilt equal to the latitude.

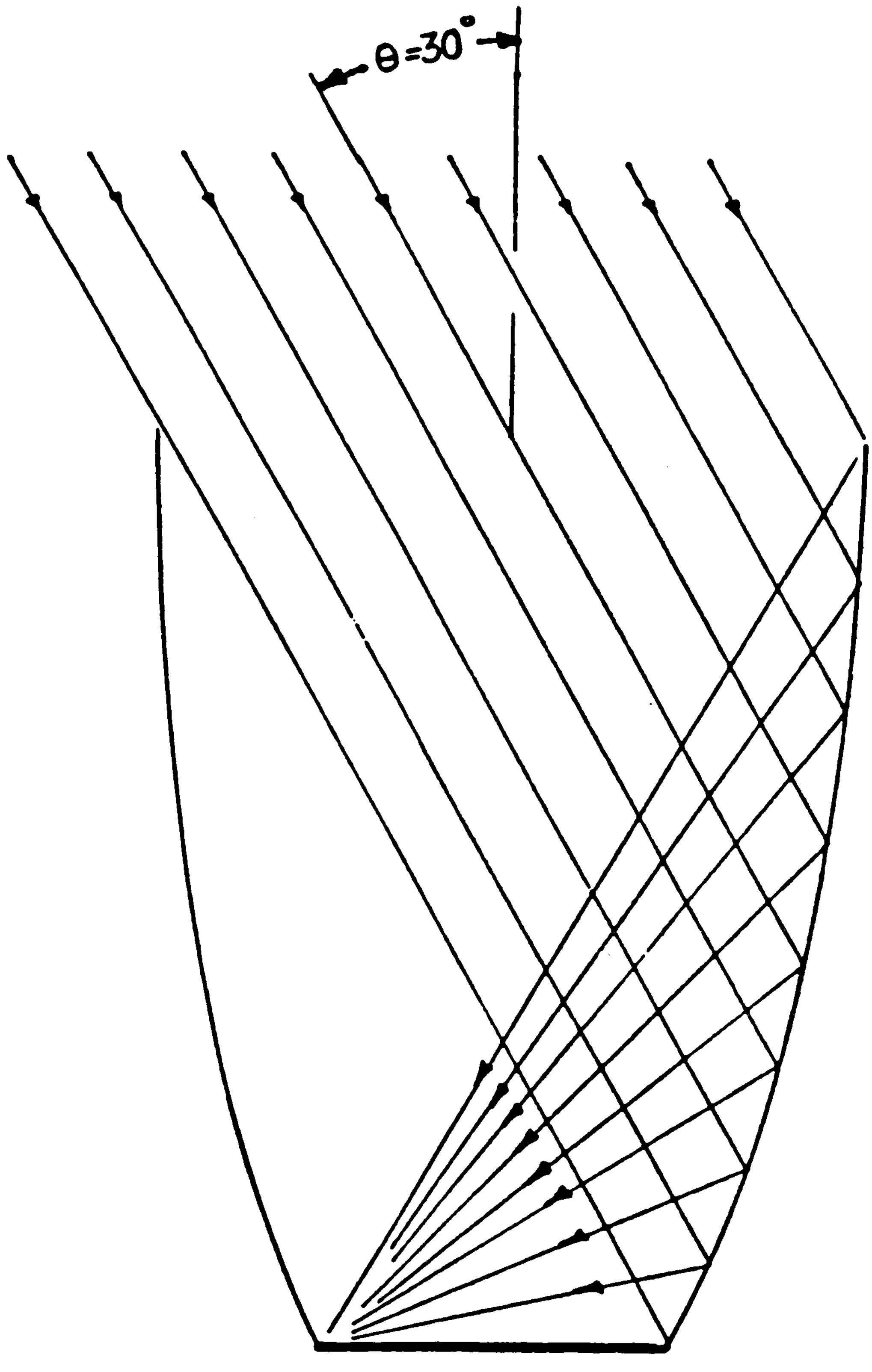


Fig. 1.2

However a parabolic cylindrical concentrator {ref.1.9} has been reported with a concentration of 14.7 attaining efficiencies of between 50 and 60%.

Another collector in this family of concentrating solar collectors is the 'V' Trough or Trapezoidal Moderately Concentrating Collector {ref.1.10}. As shown in Fig.1.3 flat mirrored sides are used instead of parabolic curves to reflect the incident solar radiation onto a selective absorber. This method has produced good results with efficiencies of 50% being reported for a receiver temperature of 93C above ambient for an optimised collector geometry. A comparison with Flat plate collectors has shown that a 'V' Trough with a groove angle of 30^{o} and a depth to base ratio of 3.23 with a selective absorber out performs a flat plate collector with the same selective surface for temperatures of 40C or more above ambient. However to obtain good performance throughout the year the depth to base ratio would have to be decreased to 1.75 which would only marginally make its performance better than the selective surface flat plate. The main disadvantage with this type of collector is once again the cost of the mirrors. Even without this extra cost it would be debatable whether this type of collector would actually collect more energy than the flat plate collector with the efficiency cross over point occurring at 40C.

1.2.4 THERMAL TRAP SYSTEMS

It has been Known for some time {ref.1.11} that if a transparent solid is irradiated by a high temperature source that the temperature of the interior insulated side gets hotter than the exposed side. The property of some materials to be transparent to solar radiation and yet opaque to thermal radiation is called the thermal trap effect. It follows that if a thermal trap is placed over an absorber, because of its high transmittance, it allows the majority of the solar energy to penetrate through to the receiving surface where it is absorbed, as shown in Fig.1.4.

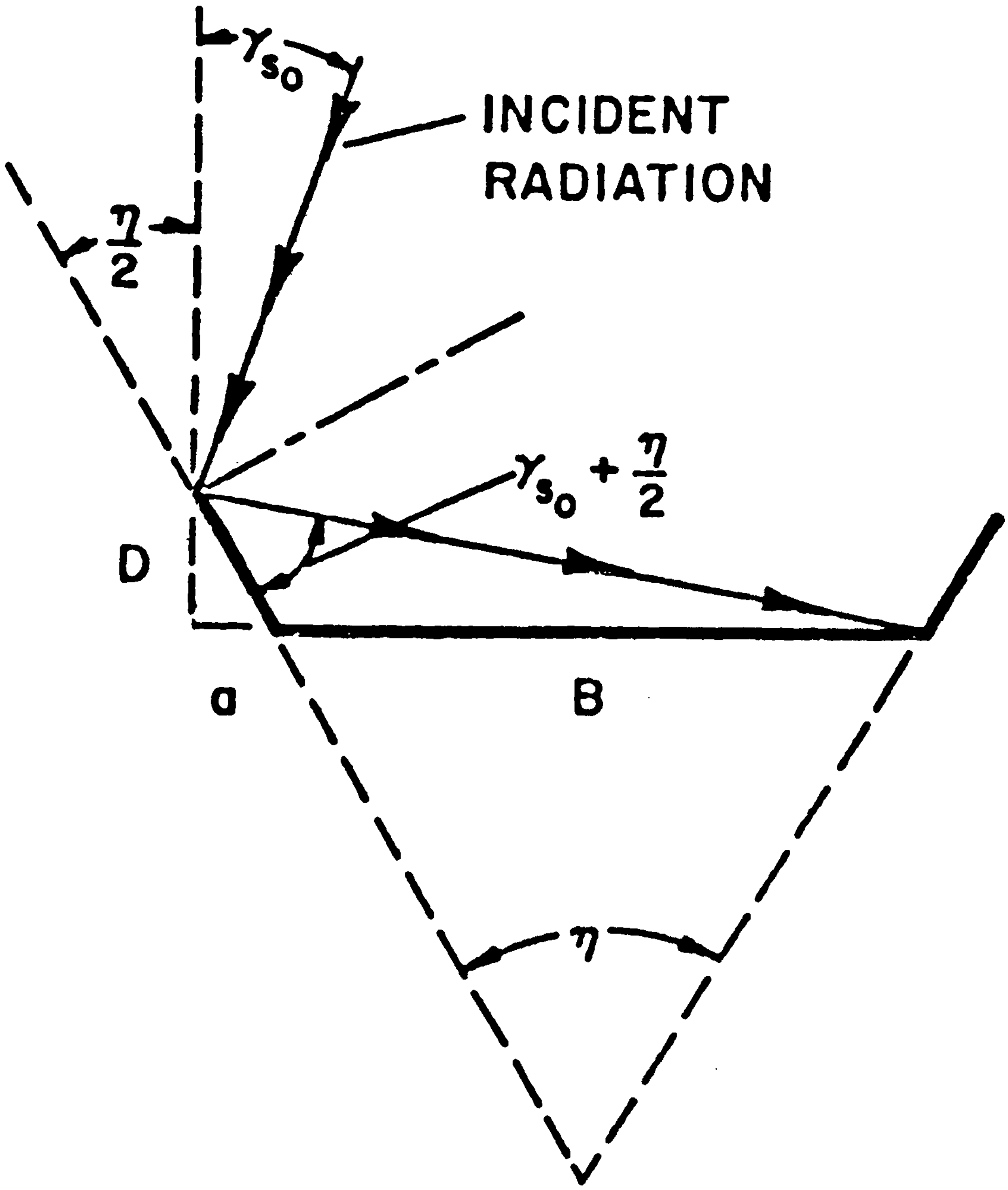
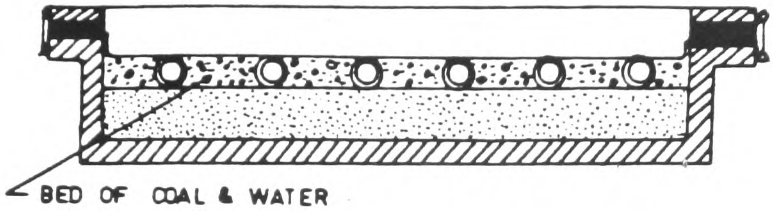
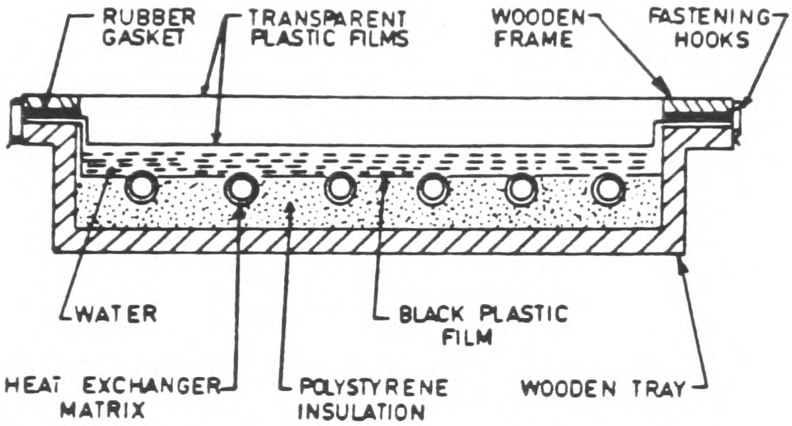
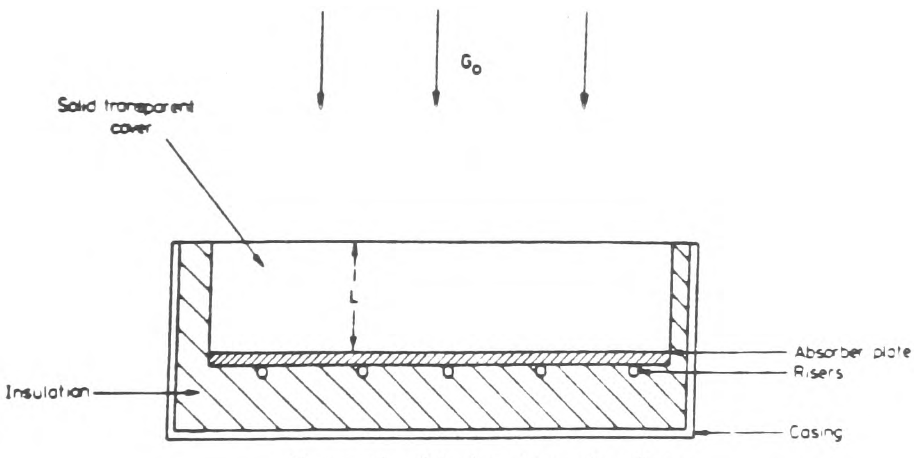

γ_{s_0}
INCIDENT
RADIATION
$\frac{\eta}{2}$
$\gamma_{s_0} + \frac{\eta}{2}$
D
a
B
η

Fig.1.3

Shallow solar pond systems with continuous heat extractions







Cross section of the thermal trap solar collector.

Fig 1.4

The Thermal radiation given off by the receiver is immediately absorbed or reflected by the trap because it is opaque to long wave radiation. A trap with a high transmittance to solar energy and a low thermal conductivity is particularly useful because it suppresses both radiation and conduction losses from the receiver.

This effect has given rise to some extensive work on solar ponds to see if the temperature increase at the bottom of the pond could be used for power generation. Solar ponds are deep natural or man-made insulated ponds (tanks) which are 2-3 meters deep of water that heats up from solar radiation. The trap effect means that the bottom of the tank increasing in temperature, however this is counteracted by convection currents set up in the water, the hot water at the bottom rising to the top where its heat is lost by evaporation and convection to air currents. To try and suppress the convection many methods have been tried and tested unfortun-ately none with any great success. The most common being the use of salt to make the solution less viscous, however this only makes the water brackish and less transparent to solar radiation and even at saturation point convection still occurs, albeit at a slightly higher temperature gradient. Another method developed to suppress convection currents was the use of parallel plastic sheets placed horizontally in the pond. Unfortuneately in practice the polythene was found to stretch and touch defeating the object. Although some new investigations have been carried out the problems of heat exchangers, convection, algae and fungi have made solar ponds less an attractive storage device than was originally thought.

Over recent years more interest has been shown in shallow Solar Ponds SSP's or SSC's {ref.1.12} but these also do not enjoy the status of flat plate collectors mainly because their technology is not so developed, not commercially available and not capable of being tilted. The fact that they have very high thermal capacities means a high proportion of of the stored energy remains unutilised. However efficiencies of 29% have been reported for continuous heat extraction for the SSC's shown in Fig.1.4.

Other comparisons between the thermal trap effect and flat plate collectors {ref.1.13} have shown that the thermal loss coefficient of the collector can be considerably reduced by this effect which benefits the collector because it is then capable of operating at higher temperatures and lower insolation levels. However for the materials studied this was at the expense of the amount of energy reaching the collector. Unfortuneatly the overall diagnosis of the performance of the trap was not favourable concluding that the high cost of the trap material impedes its use although theoretically such a collector could perform better than a flat plate collector. The feasibility of such a system would only become possible if materials with a suitable combination of absorptance, thermal conductivity, temperature tolerance and cost become available.

1.3 THE PROPOSED CONCENTRATING SOLAR TRAP

1.3.1 COLLECTOR CONSIDERATION

The systems outlined in the introduction have served to indicate some of the advantages, disadvantages and features that are inherent in those collector designs although their common aim has been to eliminate heat loss from the receiver. In particular the thermal trap overcame the problem of heat loss by radiation but reduced the amount of energy reaching the receiver. Concentrating systems demonstrated that high concentrations became very beam dependant but for moderate concentrations both beam and diffuse radiation could be collected without tracking. The smaller receiver area giving rise to higher grade heat and smaller heat losses. The trapezoidal collector showed that a non-focussing concentrating collector could perform equally as well if it was properly optimised. Intuitively it would seem that a collector that could combine all these attributes could lead to a new class of efficient solar collector that could out perform existing designs. This then has lead to the present investigation into the development of a concentrating solar trap.

1.3.2 THE PROPOSED TRAP MATERIAL

The refinement of Polybutene has lead to a range of transparent liquids (trade named Hyvis) that has lead to this regenerated interest in solar traps. Hyvis 2000 so called because it has a viscosity of 2000 ssu. at 100C is sufficiently viscous as to not cause heat loss by convection and for the purposes of the heat loss calculations can be assumed to be solid. Hyvis is a clear semi-transparent hydrocarbon liquid, which for temperatures up to 150C is fairly stable and inert to most other substances (a full list of Hyvis properties are listed in section 4.3). Becides having a high transmittance to solar radiation Hyvis has a thermal conductivity of 0.16 $Wm^{-1}C^{-1}$ which means it has quite good insulation properties. Therefore a thermal trap using Hyvis would have very low heat loss characteristics having only a minimal loss caused by conduction and of the same order as back and side losses. Experiments carried out by Brown {ref.1.14} at the Polytechnic of Wales predicted that the transmittance of solar energy in Hyvis was as high as 76% through an 0.08m cell, indicated that very favourable collector efficiencies could be obtained using this material. Therefore Hyvis is a potentially useful trap material and certainly worthy of further consideration.

1.3.3 THE COLLECTOR GEOMETRY

Once it had been decided to develop a concentrating solar collector, the best method of producing the concentration was analyzed. Previous concentrator designs as discussed in section 1.2.3 all have effective absorption limitations, either in optical geometry or transmittance, reflectance and absorptance. The underlying question was, had other shapes been overlooked, and if so how would the new shape respond to previously exhibited problems in other concentrators.

By considering the Parabolic collector it was apparent that the reflecting surface near the receiver should be almost normal so as to discourage large incident angles.

Another fact highlighted by the trapezoidal collector was that the angle of the plane of the reflecting surface near the rim predicts the acceptance angle of the incident radiation. This implies that the angle subtended by the tangents to the reflecting surfaces near the rim should be as large as possible. However these preminitions are not prerequisites that imply that the collector efficiency would be improved by theie implementation but merely serve as indicators of limitations experienced with other collectors.

In the search for a superior geometry consideration was given to parallel analogies in other areas of physics such as that used for sound concentration and dispersion. The idea of a Trumpet shaped collector was then envisaged satisfying both the previous requisites and containing a smaller volume than either the trapezoidal or parabolic collectors. An investigation into a two dimensional shape as opposed to its three dimensional counterpart was preferred as only relatively low concentrations are required. It was also anticipated that a two dimensional model would simplify the manufacture of the optimised collector as well as simplifying the ray tracking in as much as there is one less component to evaluate. By consideration of the direction cosines in three dimension space it is found that the components in a two dimensional plane, which could be the cross sectional plane of the collector (sagital plane), are unaffected by the component in the third dimension. Of course if concentration did occur in the axial plane then the concentration would be the square of the two dimensional value. However it is almost impossible to devise a three dimensional collector that does not require tracking because of shadowing on the receiver.

It only remained to choose the type of curvature that would be used for the reflecting surfaces to complete the analysis of the collector geometry. The choice being circular, parabolic or hyperbolic. It was decided that circular curves would be used for an initial investigation as this would simplify the mathematical model and be easier to manufacture the resulting collector.

It was also decided that the top would also be circular as this would have the effect of concentrating the solar radiation onto the receiver which may imply that the top curvature is optimised by the depth of the collector. It was also envisaged that at a latter date, other types of curvatures for the top and reflecting sides could be tried, optimised and tested. The overall effect of both top and side reflecting surfaces can be described as a radiation funnel that requires optimising, as shown in Fig.1.5.

1.4 THE DEVELOPMENT OF A CONCENTRATING SOLAR TRAP

1.4.1 AGENDA OF DEVELOPMENT

The details of this thesis has been modularised to try and give a coherent structure with a planned and organized code of research. To aid clarity the following discrete elements have been devised as necessary steps to accomplish the development work.

1. The optimisation of the collector geometry.

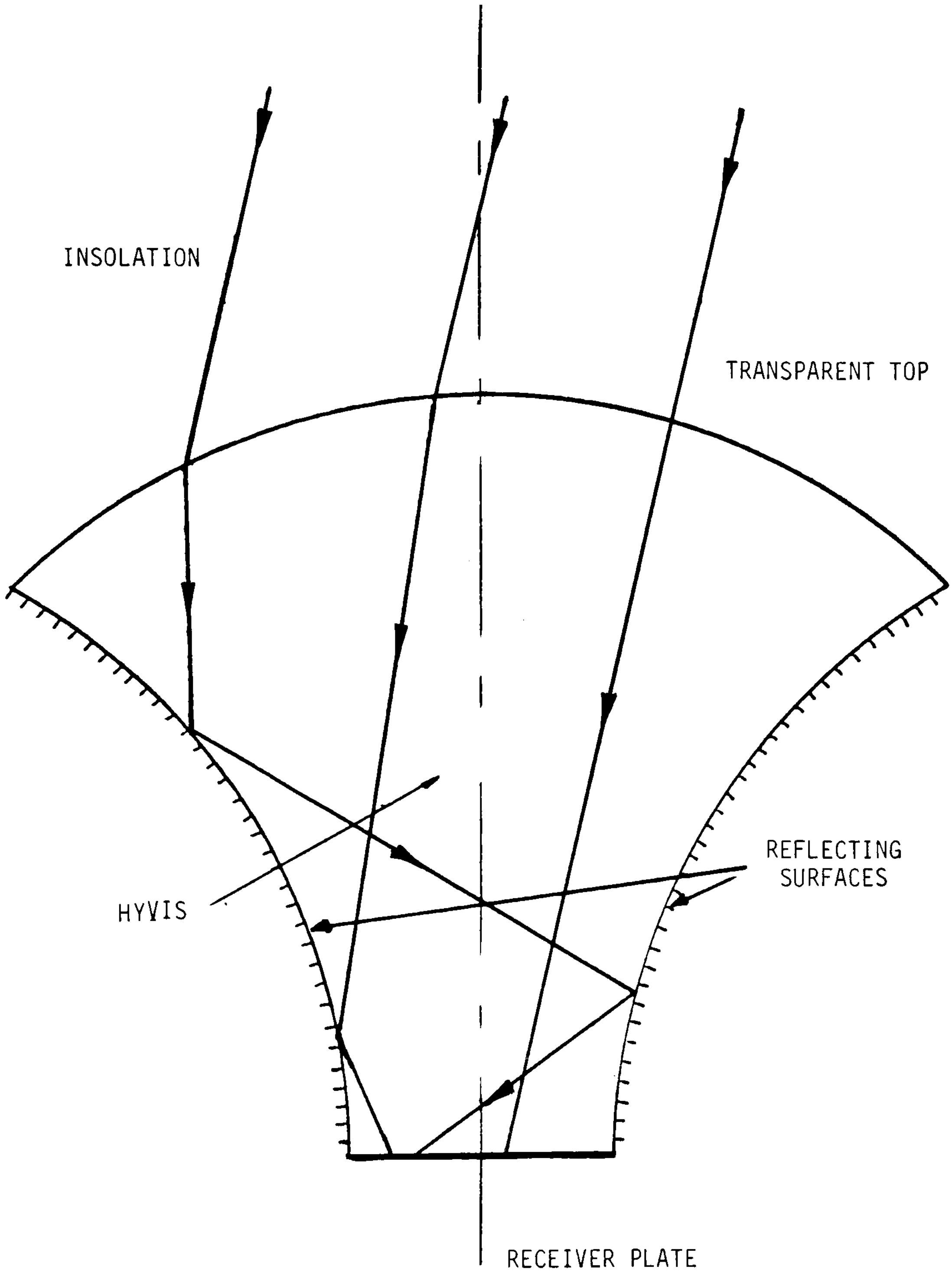
2. Manufacture the optimised collector.

3. Test and predict the collector efficiencies.

1.4.2 THE OPTIMISATION OF THE COLLECTOR GEOMETRY

The optimisation can be divided into two areas of concern, the optical efficiency of the collector geometry and the heat loss from the receiver, from which predictions of collector efficiency can be made.

In the design stage of any experimental apparatus preliminary computation is often quicker and more helpful, in that the amount of experimentation can be significantly reduced.



CROSS SECTION THROUGH A CONCENTRATING SOLAR TRAP

Fig. 1.5

The optimal prediction will therfore contain a combination of computational and experimental work.

The optimisation therefore consisted of a computer simulation that predicted the optical efficiency of various top and side curvatures for different depth and receiver widths. For each of the 1500 optical efficiencies reviewed an approximate heat loss calculation for the conduction across the collector, with known temperature differences between the receiver plate and the ambient temperature, was evaluated. The optimum collector geometry was then chosen by careful consideration of the efficiency and heat loss coefficient together with an estimate of the cost effectiveness of each collector considered.

In order to ver ify the optical efficiency of the chosen collector a ray tracking experiment was devised using a lazer beam and collector geometries made from perspex. From the resulting ray paths the acceptance angles predicted in the simulation were tracked and photographed.

The heat loss for the optimum geometry was then more accurately assessed by a simulation for both steady and unsteady state conditions. The heat loss so far had only been analysed assumming no energy absorption in the Hyvis and no heat loss through the insulation. These assumptions vastly simplify the actual situation since approximately half of the incident radiation is absorbed in the Hyvis which can be as much as 30W per metre length of collector on a clear day. Whereas the conduction losses through the Hyvis of about 3W are roughly the same for the insulation. The new simulation for the heat loss takes into account both of these factors. This was acheived by the adaptation of the finite difference method of heat transfer where the energy balance of discrete elements are used to analyse the temperature distribution throughout the collector. The main drawback of the method was the length of computer time required to solve the solution matrices.

1.4.3 THE MANUFACTURE OF THE COLLECTOR

Once the optimisation was complete the design and construction of the collector was undertaken. An assessment of the collector physical requirements such as temperature ranges and dimensional considerations was instigated along with an analysis of absorptances, reflectivities, thermal conductivities, thermal masses and operational temperatures of appropriate manufacturing materials. It was envisaged that the maximum working temperature of the collector could reach boiling point although the normal operational temperature of the collector would never be required to heat the water greater than 80C. Of course to a great extent this would depend on independant factors such as storage tank capacity and the availability of insolation.

The theoretical stagnation temperature of the collector of 410C suggests that higher temperatures could be acheived under extreme conditions. This of course does not account for the reduction in viscosity of the Hyvis in the collector which is likely to start convecting at about 140C. The operational maximum temperature of the materials used for the collector were therefore set at 140C. Once the choice of the collector materials had been made the itinary and components of the collector was prepared and assembled. The collector consisted of three parallel channels contained in a wooded box with a glass cover. The reflecting surfaces were constructed from aluminised-polyester film while the heat exchange system was made from ordinary domestic copper pipe. The completed collector being filled with Hyvis.

1.4.4 TEST AND PREDICT THE COLLECTOR EFFICIENCIES

The collector was then in a position to be tested. The apparatus required to test the collector under transient conditions was already available at the Polytechnic of Wales so the equipment was set up and for various input temperatures the collector was tested. From the recorded data graphs of efficiency, power inputs and outputs and all the required temperatures were drawn.

The experimental steady state values being obtained from these graphs. These steady state values were then compared with the predicted simulated values for verrification. From the simulation for the unsteady state and the experimental results of the collector cooling an estimate of the time constant of the collector was obtained.

1.5 COMPARISONS AND CONCLUSIONS

Finally an assessment of the collector performance and a comparison with other types of collector was undertaken. This critical analysis indicated that the transmission characteristics of Hyvis undertaken by Brown were inappropriate for depths greater than 0.04m and certainly incorrect for the depths of Hyvis used in the collector, however reasonably good agreement was possible for the heat loss characteristics. Subsequent retesting of the transmission of Hyvis for depths up to 0.30m has shown a reduction of 20% off the original data used for the optimisation. This has lead to the conclusion that the optimisation should be repeated for the revised transmission values. However although efficiency improvements could be made it seems unlikely that the outcome would predict efficiencies better than an evacuated type collector. This analysis also incorporated elements or areas where further research, development and optimisations would be advantagous for a more complete evaluation. However the results have indicated that the simulation was infact accurate and that further geometric simulations could be tried using this model with full confidence. In total the project had more potentially undeveloped implications at its conclusion than were ever present at its onset.

REFERENCES.

1.1 J.F.Duffie and W.A.Beckman, Solar Energy Thermal Processes (1974).

1.2 H.S.Shiers, Sealing Of Partially Evacuated Solar Collectors. M.Phil Poly. of Wales. (1986).

1.3 G.T.Roberts, Heat loss Characteristics Of An Evacuated Plate-in-tube Collector. Solar Energy 22,137 (1979).

1.4 R.Winston, Principles Of Solar Concentrators Of A Novel Design. Solar Energy 16,89 (1974).

1.5 H.Tabor, Comment-The CPC concept-theory and practice. Solar Energy 33,629 (1984).

1.6 M.J.Carvalho, M.Collares-Pereira, J.M.Gordon and A.Rabl, Truncation Of CPC Solar Collectors And Its Effect On Energy Collection. Solar Energy 35,393 (1985).

1.7 H.P.Baum and J.M.Gordon, Geometric Characteristics of Ideal Nonimaging (CPC) Solar Collectors With Cylindrical Absorber. Solar Energy 33,455 (1984).

1.8 D.I.Jarrar and S.a.Moustafa, Geometrical Effects On The Performance Of Trough Collectors. Solar Energy 30,109 (1983).

1.9 R.V.Heiti and G.Thodos, An Experimental Parabolic Cylindrical Concentrator: Its Construction and Thermal Performance. Solar Energy 30,483 (1983).

1.10 R.B.Bannerot and J.R.Howell, Moderately Concentrating Flat-Plate Solar Energy Collectors. AICHE-ASME 11,1 (1975).

1.11 M.H.Cobble, Irradiation Into Transparent Solids And The Thermal Trap Effect. J.Franklin Inst. 278,383 (1964).

1.12 V.N.Kishoe, M.R.Gandi and K.S.Rao, Experimental And Analytical Studies Of Shallow Solar Pond Systems With Continuous Heat Extraction. Solar Energy 36,245 (1986).

1.13 J.P.Kenna, The Thermal Trap Solar Collector. Solar Energy 31,335 (1983).

1.14 S.Brown, Polytechnic of Wales private communication (1980).

CHAPTER 2

OTIMISING COLLECTOR EFFICIENCY

2.1 INRODUCTION

In this chapter a simulation of collector performance is undertaken with the aim of optimising the efficiency of the collector. This is achieved by a simulation of ray tracking through the collector and a comparison of all the shapes considered will optimise the shape of the collector.
It is necessary to appreciate that energy enters the collector by way of radiation which is emitted by the sun and absorbed by a receiver or absorber plate within the collector. The majority of this energy is dissipated in the form of heat and is collected by a transfer medium such as water for some useful purpose like heating a domestic hot water supply. The amount of heat transfered to the water supply is the energy gained by the collector and therefore collector efficiency can be defined as:-

$$n = \text{energy gain/incident energy.}$$

The energy gain of a collector can be considered to consist of the energy reaching the receiver minus the heat loss from the receiver. The energy reaching the receiver is dependant on the optical efficiency of the collector while the heat loss is dependant on the collector geometry and the collector's working temperatures, namely the receiver and the ambient temperatures. It is therefore necessary to define what is meant by optical efficiency and how it relates to the cost effectiveness of a collector. The term optical efficiency refers to the proportion of insolation incident on a collector that reaches the receiver, and is inherently a function of the collectors shape and the physical properties of the materials used in its construction. This is perhaps an appropriate place to clarify the difference between magnification as defined in section 1.2.3, concentration and optical efficiency defined above.

Concentration being the resultant of both magnification and optical efficiency and is therefore defined as the ratio of insolation per unit area incident on the collector to that at the receiver:-

Concentration = Magnification * Optical Efficiency.

The energy gain of a collector however is both a function of optical efficiency and heat loss from the receiver and it is our intention to optimise these two functions so as to produce the best possible collector efficiency. Therefore besides optical efficiency and magnification it will be necessary to consider how the heat loss and subsequent collector efficiency changes with varying climatic conditions.

The simulation of optical efficiency will predict the energy reaching the receiver as a percentage of the incident energy and together with a simplistic heat loss model for various weather conditions can be used for the optimisation of the collector geometry. The optimisation will also include an evaluation of manufacturing cost per unit energy gain, because in the final analysis production costs will play a significant part in its commercial viability. So for this purpose it will be assumed that the manufacturing costs are proportional to the volume of Hyvis used to fill the collector.

In the analysis of a number of interacting known phenomena, computation performs more efficiently than experimentation, but even then the computed simulation will require validation by comparison with experimental results. The objective is to simulate the optical efficiency by the use of a computer model from which the performance of a number of different geometries under various operating conditions can be analysed. Further experimentation and validation of the predicted shape can then be carried out. The experimentation will consist of two parts, firstly the verification of the ray tracking simulation and secondly the evaluation of collector efficiency under day to day working conditions.

This chapter considers the optical efficiency and approximate heat loss for some 1500 different geometries of which 440 have been evaluated and compared. From these estimated collector efficiencies, one collector has been chosen for further investigation and verification of its predicted collector efficiency.

2.2 COLLECTOR SHAPE SPECIFICATION

2.2.1 THE SIMULATION

The simulation required for the optimisation of the collector shape must be capable of ray tracking and evaluating the collector efficiency, for various weather conditions, and for all the shapes to be considered.

The simulation should therefore consist of:-

(a) A means of changing the shape of the collector by mathematically defining its boundary surfaces and varying the incident angle of the solar radiation.

(b) A method of tracking all incident radiation so as to establish the percentage of incident energy reaching the receiver.

(c) An evaluation of the heat loss for various operating conditions.

(d) A presentation of the results of each shape giving percentage efficiencies for each angle of incidence considered.

(e) An evaluation of the volume of the collector per unit of collector area.

These objectives can be subdivided into a number of tasks and associated assumptions that simplify and clarify each point.

In order to facilitate the setting up of the various collector geometries and varying the direction of the incident solar radiation, the following assumptions have been made, namely:-

1. That the collector shape will be of the track type with a symmetrical cross section, see Fig.2.1. This will simplify much of the mathematical rigor required and will help in fault finding as results from each half of the collector can be compared.

2. The collector boundary will consist of four separately defined surfaces. These being the two side reflecting surfaces, the top and absorbing surfaces as shown in Fig.1.5.

3. The receiver plate will be flat and parallel to the plane of the collector see Fig.2.1. This simplifies the total geometry of the collector and the collector efficiency calculations.

4. The top and side surfaces will be curved and circular. It may well be that the choice of curvature would be better being parabolic or eliptic but it is felt that for this initial investigation it would be easier to limit the choice.

5. Any shape with a concentration less than two will be ignored. This premise stems from the belief that magnifications less than two are hardly worth the extra cost.

An infinite variation of the collector geometry is possible hence an investigation of various potential collector shapes was undertaken by setting up an algorithm, which varies the curvature and position of the collectors boundaries. The tasks required in performing this algorithm can be itemised as follows with reference to Fig.2.2:-

A CONCENTRATING SOLAR TRAP

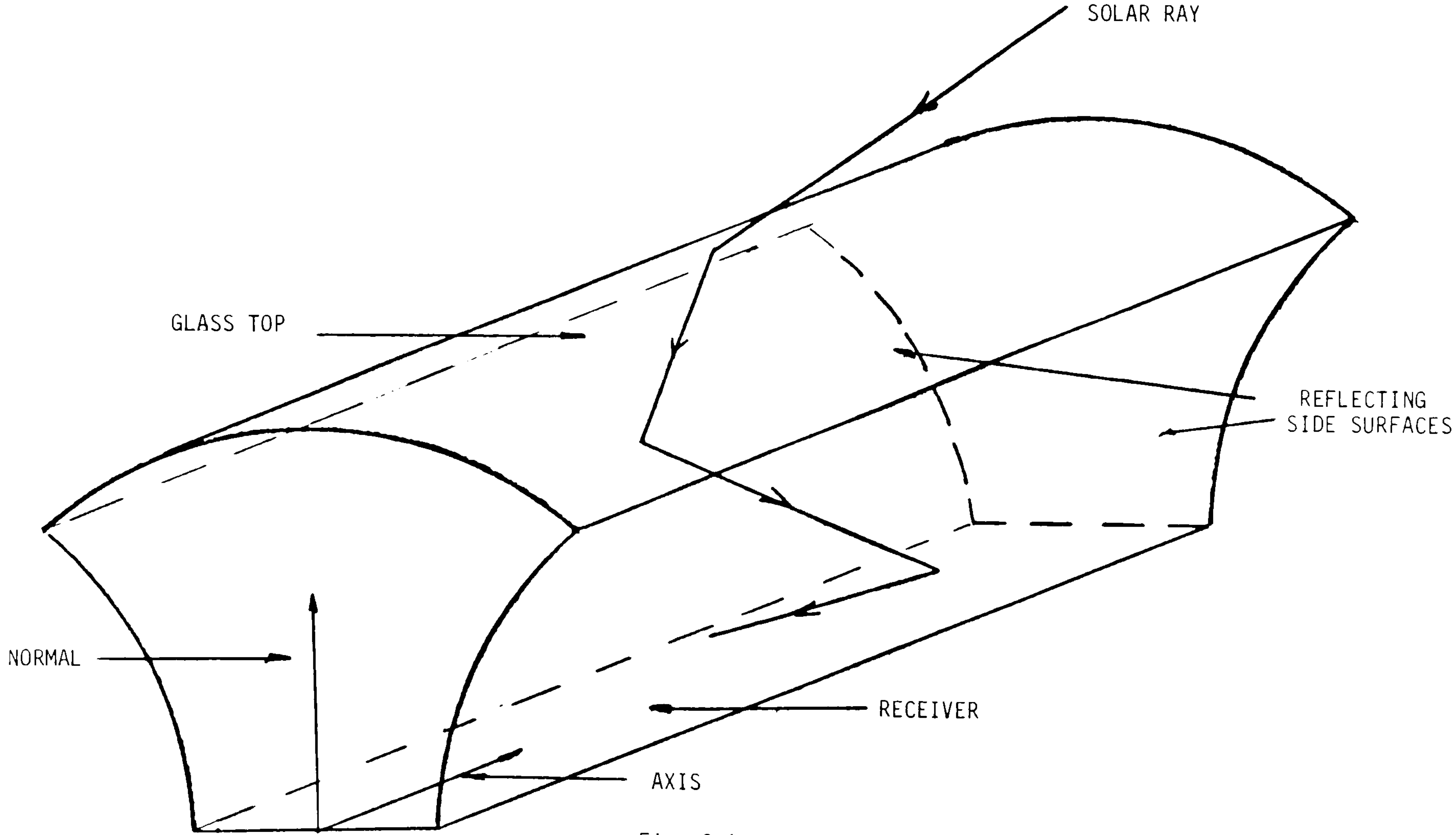


Fig. 2.1

THE COORDINATE SYSTEM OF THE COLLECTOR GEOMETRY

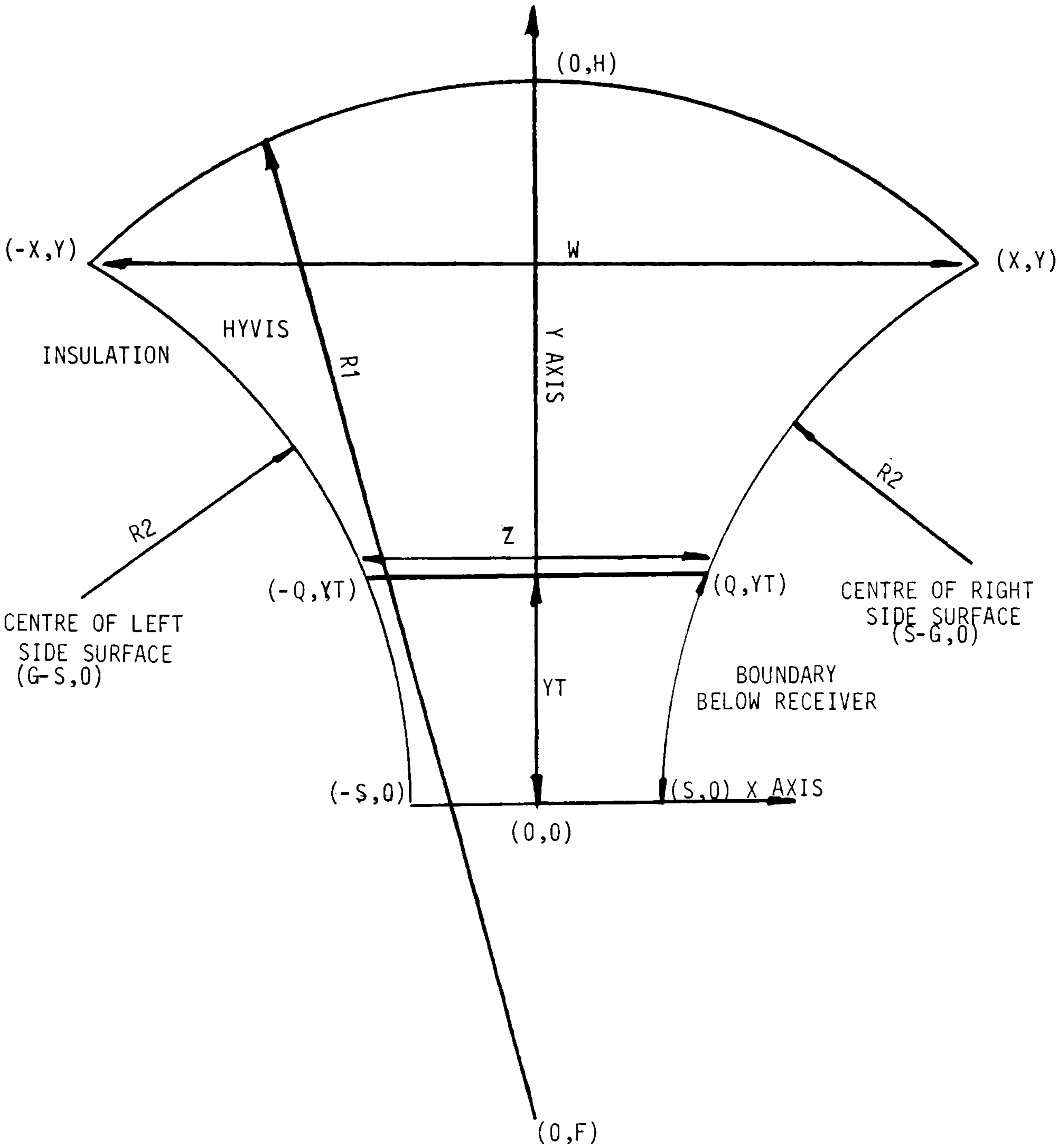


Fig 2.2

1. Varying the curvature R1 of the top surface in steps from 100mm to approximately 5000mm radius (almost flat).

2. For each top curvature vary the vertical height F of its centre.

3. For each top surface vary the curvature R2 of the side surfaces in steps from 100mm to approximately 4000mm radius (almost flat).

4. For each side curvature vary the horizontal position of the centre of curvature (S-G).

5. For each centre of curvature vary the height H between the receiver surface and the top surface.

6. For each collector shape vary the angle of the solar beam in steps of 5° from -30° to $+30^{\circ}$ from the normal.

For each case considered it is necessary to track all incident radiation between the top surface and the receiver. The Hyvis used within the trap will absorb a considerable amount of incident energy and consequently the optical efficiency involves determining the optical path lengths and subsequent beam attenuation within the Hyvis. Therefore to establish the percentage of incident energy reaching the receiver the following is necessary:-

1. For each angle of incidence of the solar beam, track each ray that enters the collector horizontally in steps of 0.10mm.

2. For each ray evaluate its track as it passes through the collector, determining which boundaries it intercepts so as to establish the number of side surface reflections, the total internal reflections on the top surface, if any, and whether it is absorbed at the receiver or returns back out to the sky.

3. Calculate the energy that is gained by the receiver. This is found by evaluating the attenuation of the rays as they pass through the Hyvis and absorption due to specular hemispherical reflectance off the side and top surfaces.

The heat loss for various operating conditions can be estimated from a simple one dimensional heat conduction model, for which it is necessary to know the solar energy flux, the rate of useful heat gained by the receiver and the temperature differential across the collector. (A more rigorous treatment of heat loss is dealt with in chapter 3 for the chosen geometry and includes the effects of the energy absorption by the Hyvis on the heat loss).

The tabulation of results for each shape consists of percentage efficiencies for each angle of incidence and includes:-

1. The definition of the shape under evaluation. This will include radii and centres of both the top and the side surfaces, the intercepts of the top and side surface and the side surface with the receiver.

2. The magnification factor of the collector.

3. The percentage of the incident rays reaching the receiver for each angle considered.

4. The percentage of energy reaching the receiver for each incident angle considered (the optical efficiency).

5. The percentage efficiencies of the collector for each incident angle considered in clear and cloudy day weather conditions at both typical winter and summer temperature differentials.

6. The evaluation of the volume of the collector per unit collector area, this is more specifically the volume that the Hyvis occupies compared to the collectors top surface area per unit length.

2.2.2 THE EQUATIONS OF THE COLLECTOR BOUNDARIES

The collector geometry can be defined by a set of equations which describe the boundary surfaces and their intercepts. These equations are as follows.

EQUATION OF TOP SURFACE:
Let us consider the shape as illustrated in Fig.2.2. To simpfify the problem it has been assumed the top surface is symmetrical about the y-axis and passes through the point (0,H) and has its centre at (0,-F).
The general equation of a circle with centre (-g,-f) is:-

$$x^2+y^2+2gx+2fy+C=0 \qquad [2.1]$$

At the point (0,H) the equation becomes:-

$$H^2+2fH+C=0$$

where

$$C=-H^2-2fH$$

therefore the equation of the top surface is:-

$$x^2+y^2+2Fy-H^2-2FH=0 \qquad [2.2]$$

EQUATION OF RIGHT SIDE SURFACE:
From Fig.2.2 it can be seen that the side surfaces are symetrical about the X-axis. The right side surface passes through the point (S,0) and has its centre at (S-G,0).

From [2.1] we have:-

$$g=G-S \text{ and } f=0$$

at the point (S,0) the equation [2.1] becomes:-

$$S^2+2(G-S)S+C=0$$

where

$$C=-S(2G-S)$$

therefore the equation of the right side surface is:-

$$x^2+y^2+2(G-S)x-S(2G-S)=0 \qquad [2.3]$$

EQUATION OF LEFT SIDE SURFACE:
From Fig.2.2 the left side surface passes through the point $(-S,0)$ and has its centre at $(G-S,0)$.

From [2.1] we have:-

$$g=S-G \text{ and } f=0$$

At the point $(-S,0)$ the equation [2.1] becomes:-

$$S^2-2(S-G)S+C=0$$

where

$$C=S(2G-S)$$

therefore the equation of the left side surface is:-

$$x^2+y^2+2(S-G)x+S(2G-S)=0 \qquad [2.4]$$

EQUATION OF THE RECEIVER HEIGHT:
From Fig.2.2 the height above the X-axis of the receiver YT can be obtained once the x coordinate of the receiver and side surface intercept has been defined. By substituting the x value into equation [2.3] we have:-

where $x=Q$

$$Q^2+YT^2+2(G-S)Q-S(2G-S)=0$$

giving

$$YT^2=S(2G-S)-2(G-S)Q-Q^2$$

It is these four boundary surface equations that are used exclusively within the algorithm to define the collector geometry.

INTERCEPT OF TOP AND SIDE SURFACES:

For the case of the intercept of the top with the right side surface equating equations [2.2] and [2.3] yields:-

$$x^2+y^2+2Fy-H^2-2FH=x^2+y^2+2(G-S)x-S(2G-S)$$

and if this is rearanged it can be reduced to:-

$$y=((G-S)/F)x+CK \qquad [2.5]$$

where the constant CK represents:-

$$CK=(H^2+2FH-S(2G-S))/(2F)$$

To obtain the coordinates of the intercept substitute equation [2.5] into [2.2], namely:-

$$x^2+(((G-S)/F)x)^2+2F(((G-S)/F)x+CK)-H^2-2FH=0$$

giving the quadratic equation:-

$$Ax^2+Bx+C=0$$

where

$$A=(1+(G-S)/F)^2$$

$$B=2((G-S)/F)(CK+F)$$

$$C=CK^2+2FCK-H^2-2FH$$

If the centre of the top surface is above the X-axis the largest root is required, and the y value will always be the largest positive value. Therefore the solution of this quadratic equation gives the intercept point (X,Y) for the top and the right hand side surfaces. The top and left hand side boundary surface intercept is simply (-X,Y) because of the symmetrical nature of the collector.

2.2.3 INTERACTION OF RAY WITH BOUNDARY SURFACES

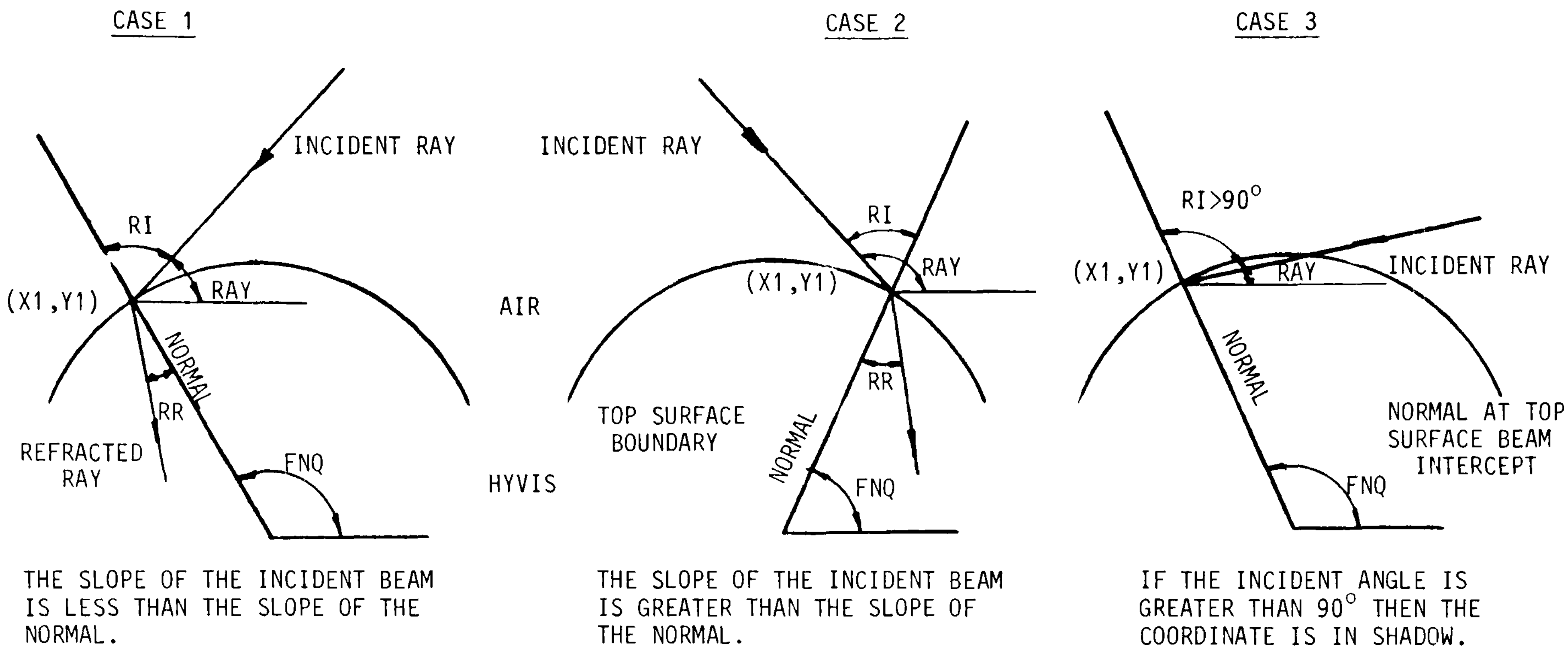
Any beam of light entering the collector can be considered as consisting of two components, namely along the axis of the collector track (z axis in Fig.2.1) and in the plane of the collector cross section (xy plane in Fig.2.1). The component of radiation along the axis can be considered as giving rise to the increased energy absorption in the hyvis normally associated with increased path length. Whereas the component in the xy plane of the collector effects energy absorption within the Hyvis, determines the number of surface reflections and controls whether or not a particular incident ray in due course reaches the receiver. It is therefore this component that needs to be ray tracked to enable the energy gained by the collector to be evaluated. Therefore for all rays entering the collector only their component in the xy plane need to be tracked.

There are three types of beam interface that are encountered as the ray passes through the collector. These are; refraction of the beam on the top surface in either direction, reflection of the beam off either of the side surfaces and total internal reflection on the underside of the top surface. At the points of intersection the new direction of the ray is determined. The ray is therefore defined by a set of equations that describes its path as it passes through the collector. These have to cater for all the possibilities that may be encountered along its path and are used exclusively to predict the optical efficiency of the collector.

REFRACTION OF SOLAR RAY WITH THE TOP SURFACE:
If x is the defined horizontal position of the incident ray on the top surface, then from equation [2.2]:-

$$y^2+2Fy+(x^2-H^2-2FH)=0$$

This equation must have positive real roots. To decide which of the two roots is correct the direction of the incident ray before it enters the collector, as shown in Fig.2.3, must first be considered.



THE DIRECTION OF THE REFRACTED SOLAR RAY ON INTERCEPTION WITH TOP SURFACE

Fig 2.3

The direction, defined as the angle between the x axis and in this case the direction of the incident ray, is denoted by the variable RAY.

It can be shown that:-

for $240<RAY<270$ the largest root is required.

while for $270<RAY<300$ the smallest root is required.

The correct root provides the required intercept (X1,Y1).

For various angles of incidence on the top surface we require the direction of the refracted ray. There are three cases to consider as shown in Fig.2.3. Case 1 where the slope of incident ray is less than the slope of the normal to the top surface at the point of interception with the ray, case 2 where the slope of incident ray is greater than the slope of the normal and case 3 where if the incident angle is greater than 90^{o} the coordinate is in shadow. A special case arises when the incident ray is normal to the surface and passes straight through the top without refracting. The normal at the point of interception can be found by differentiating equation [2.1] giving:-

$$dy/dx=-\{(x+g)/(y+f)\}$$

and the normal

$$=-1/(dy/dx)$$

therefore the angle of the normal is:-

$$FNQ=\tan^{-1}\{(y+F)/(x+G)\}$$

Once the coordinates of the intercept (X1,Y1) and the new direction of the ray (RAY) have been calculated. The equation of the new paths line of action can be defined. Where RFFM is the slope and RFFC the y axis intercept of its equation. We have:-

$$RFFM=\tan\{RAY\}$$

and

$$RFFC=Y1-(RFFM)*X1$$

The equation of the new path for the refracted ray becomes:-

$$y=RFFMx+RFFC$$

Throughout the simulation the ray is defined by an equation of a straight line, however it is not sufficient to merely know this line of action to define the ray for its direction is also required. The ray can therefore be completely described by the variable RAY, the direction of the ray in degrees, and either RFFC the y axis intercept of the equation of the ray's line of action or the coordinates of the point of interception. The equation of the ray's line of action is given by:-

$$y=RFFMx+RFFC \qquad [2.6]$$

INTERCEPT OF SOLAR RAY WITH TOP SURFACE:

To obtain the intercept of the solar ray with the top surface the equation of the ray [2.6] is substituted into equation [2.2]. Therefore the equation of the ray's intercept with the top surface is defined as:-

$$x^2+(RFFMx+RFFC)^2+2F(RFFMx+RFFC)-H^2-2FH=0$$

giving the quadratic equation:-

$$Ax^2+Bx+C=0$$

where

$$A=1+RFFM^2$$

$$B=2RFFM(RFFC+F)$$

$$C=RFFC^2+2F(RFFC-H)-H^2$$

This quadratic equation must have positive real roots. To decide which of the two roots is correct the direction of the incident beam, denoted by RAY, must first be considered.

Then for:-

$0<RAY<90$ or $180<RAY<270$ the largest root is required.

and if the path actually started from the top surface a check must be used to make sure the starting and finishing points are not the same. Otherwise the smallest root is required. This root which is really the x coordinate of the required intercept will then lie somewhere on the top surface. If the root is called X2 then this would mean that:-

$$-X<X2<X$$

Once the x coordinate has been fully validated the cooresponding y coordinate must also lie within its required range, see Fig.2.2.

$$Y<Y2<H$$

INTERCEPT OF SOLAR RAY WITH SIDE SURFACES:
To obtain the intercept of the solar ray with the right hand side surface the equation of the ray [2.6] is substituted into equation [2.3] yeilding the following equation:-

$$x^2+(RFFMx+RFFC)^2+2(G-S)x-S(2G-S)=0$$

giving the quadratic equation

$$Ax^2+Bx+C=0$$

where

$$A=1+RFFM^2$$

$$B=2RFFM.RFFC+2(G-S)$$

$$C=RFFC^2-S(2G-S)$$

For the intercept to exist this equation must have real roots and the correct root is obtained by consideration of the direction of the incident beam.

Then for:-

	$180<RAY<270$	the largest root is required.
and		
for	$90<RAY<180$	there is no intercept.

otherwise the smallest root is required. This root which is really the x coordinate of the required intercept will then lie somewhere on the right hand side surface If the root is called X2 then it should be checked that:-

$$S<X2<X$$

Using a similar treatment for the left side surface reveals the following quadratic equation:-

$$Ax^2+Bx+C=0$$

where

$$A=1+RFFM^2$$

$$B=2RFFM.RFFC+2(S-G)$$

$$C=RFFC^2+S(2G-S)$$

As before the required root will depend on:-

for	$90<RAY<180$	the largest root is required.
and		
for	$0<RAY<90$	there is no intercept.

otherwise the smallest root is required and must lie within the range:-

$$-X<X2<-S$$

REFLECTION ON THE SIDE SURFACE:

Once an intercept with a side surface has been established the new equation of the line of action and direction of the ray caused by reflection can be found.

This task is comparitively straight forward, for once the normal to the surface at the intercept FSNQ has been calculated together with the direction of the ray before reflection, the new direction and subsequent equation can be obtained. Fig.2.4 shows how the direction (RAY) of the reflected ray can be determined in terms of the incident beam. In the simulation this is handled by the subroutines RAYJ1.FOR for reflection on the left hand side surface and RAYJ2.FOR for reflection on the right hand side surface.

TOTAL INTERNAL REFLECTION ON THE TOP SURFACE:
If the incidence angle for an intercept on the top surface is greater than 41.5^{o} then from Snell's Law the ray is totally internally reflected otherwise the ray will escape back to the sky. The new path of the ray can be determined from the normal to the top surface at the intercept FNQ, the intercept coordinates and the direction of the incident beam. The new RAY can then be evaluated in a similar manner to that used for the side surfaces as shown in Fig.2.4.

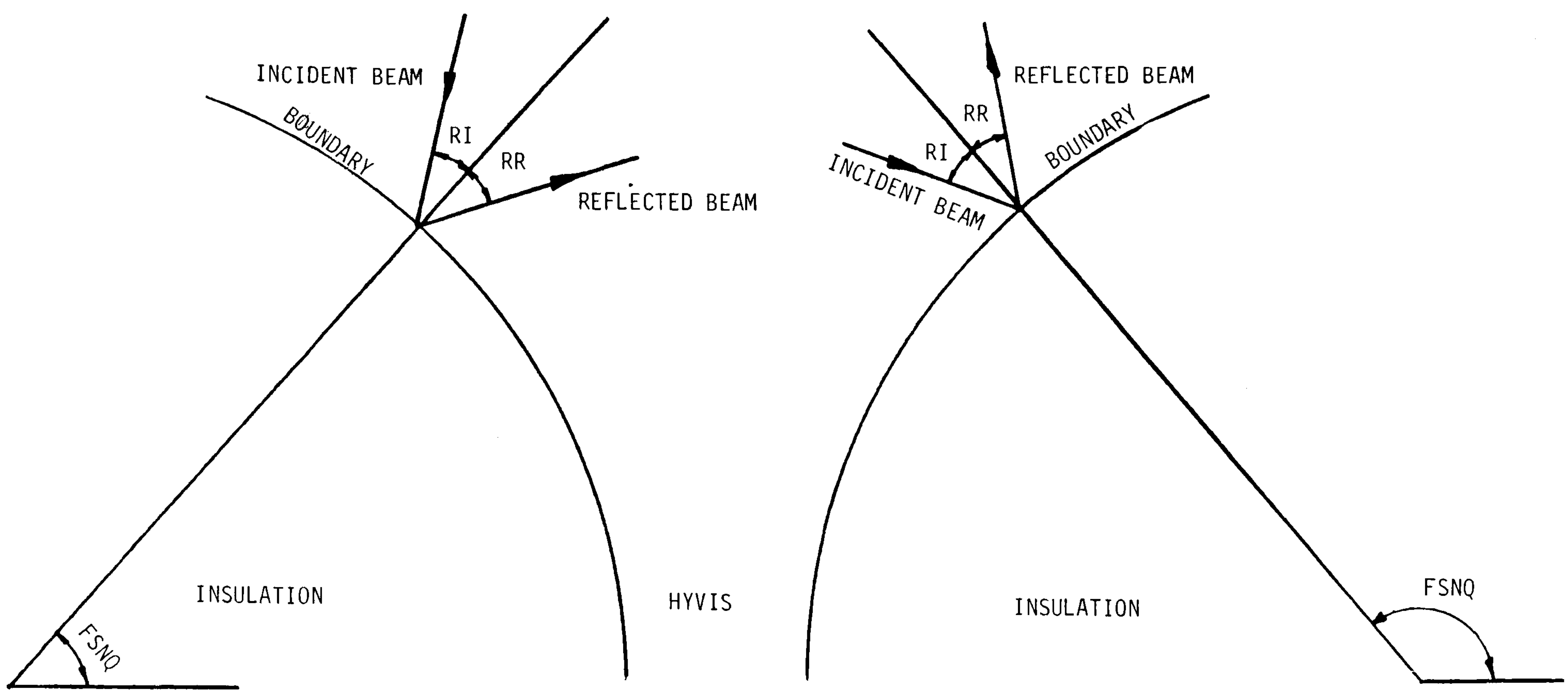
2.2.4 CALCULATION OF HEAT LOSS FOR VARIOUS OPERATING CONDITIONS.

As has been explained in the introduction to this chapter it is not possible to predict the efficiency without an appreciation of the heat loss from the collector. A detailed evaluation of heat loss using a quantitative method is not possible because of the complexity of shape and because of the many contributing factors at the boundaries. In chapter three an analytic model of the heat flow has been developed but at this stage it is sufficient just to appreciate the order of magnitude of the heat loss to enable the collector efficiency and its subsequent optimisation to be carried out. Therefore a qualitative method has been developed with wide sweeping assumptions that will simplify the evaluation. In particular these are:-

1. Heat loss only occurs from the top surface with the other boundaries assum~~m~~ed to be adiabatic.

INTERCEPT/REFLECTION ON LEFT SIDE SURFACE

INTERCEPT/REFLECTION ON RIGHT SIDE SURFACE



TO CALCULATE THE DIRECTION AFTER REFLECTION (RAY) FROM DIRECTION BEFORE REFLECTION (RAY).

RAY = 2 FSNQ - RAY + 180
IF RAY <0° THEN
RAY = RAY + 360

RAY = FSNQ - RAY + 180
IF RAY <90° THEN
RAY = 2 FSNQ - RAY - 180
AND IF RAY <0° THEN
RAY = RAY + 180

Fig 2.4

2. Heat energy absorbed by the Hyvis is neglected.
3. The section through the collector is treated as one dimensional.
4. Prescribed temperature boundaries for trap and receiver surfaces.

From Fig.2.2. and otherwise :-

Qi	=	Total power incident on collector	(W).
Qr	=	Total power reaching the receiver	(W).
Ql	=	Total power lost from receiver	(W).
E	=	Insolation on collector top	(Wm^{-2}).
W	=	Width of the collector top	(m).
Z	=	Width of the receiver	(m).
H-YT	=	Depth of the collector or Hyvis	(m).
p	=	Fraction of energy reaching the receiver.	
k	=	Thermal conductivity of Hyvis	($Wm^{-1}C^{-1}$).
DT	=	Temperature difference between the receiver plate and the surroundings.	

For a track of length 1m.

$$Qi = WE$$

and

$$Qr = WEp$$

Therefore if the power lost by one metre of receiver is approximated as being one dimensional heat transfer by conduction then one model for its evaluation could depend on the receiver width, the depth of the Hyvis and the receiver and ambient temperatures.

then from:-

$$Q = kAdT/dx$$

we have:-

$$Ql = kZDT/(H-YT)$$

Therefore the power gained by the receiver is:-

$$Qg = Qr-Ql = WEp - kZDT/(H-YT)$$

and from its definition the collector efficiency is:-

$$n = Qg/Qi = p - \{kZ/W(H-YT)\}DT/E$$

Consequently the slope KQ for the graph of n against DT/E becomes:-

$$KQ = kZ/W(H-YT)$$

which is the heat loss coefficient of the collector.

Further it is possible to calculate the efficiencies of each shape if the value of DT/E is known. This can be estimated for known weather conditions.

If we define:-

$$K' = kDT/E$$

then:-

$$n = p - \{Z/(H-YT)\}K'$$

For various climatic conditions only the value of k' will change in the efficiency equation. In the simulation the collector efficiencies will be evaluated for the four climatic conditions below.

	DT	E	K'
a)	40	100	0.04
b)	40	600	0.0067
c)	80	100	0.08
d)	80	600	0.013

It must be remembered that this estimate of heat loss is only intended to give an appreciation of its order and effective change on the efficiency. For example the heat loss by this model would be approximately the same for all shapes of the same depth to receiver width.

2.2.5 EVALUATION OF THE VOLUME WITHIN THE COLLECTOR

From the cross sectional area of the collector the volume can be quoted per unit length. The cross sectional area, cross hatched in Fig.2.5, consists of a composite of elemental areas which can be calculated separately. From Fig.2.6 the composite can be divided into two elements. AREA1 the area between the top surface and the y coordinate of the receiver and AREA2 the area between the side boundaries and the y coordinate of the receiver. The collector cross sectional area is then (AREA1)-2(AREA2).

The area defined by the curve $x^2+y^2=r^2$, the x-axis and boundaries x=a and x=b is:-

$$\text{area} = \int_a^b (r^2-x^2)^{0.5}\, dx$$

which can be evaluated as:-

$$\text{area} = 0.5\left[xy+r^2\sin^{-1}(x/r)\right]_a^b \qquad [2.7]$$

and between the limits x=-x and x=x this is simply:-

$$\text{area} = xy+r^2\sin^{-1}(x/r)$$

Therefore refering to Fig.2.6 the area under the top surface and between the intercepts becomes:-

$$\text{area} = X'Y'+r^2\sin^{-1}(X'/R1)$$

Where R1 is the radius of the top surface and X'= X the value of Y' can be found from:-

TO EVALUATE THE VOLUME CONTAINED WITHIN THE COLLECTOR BOUNDARIES

CROSS SECTION OF COLLECTOR

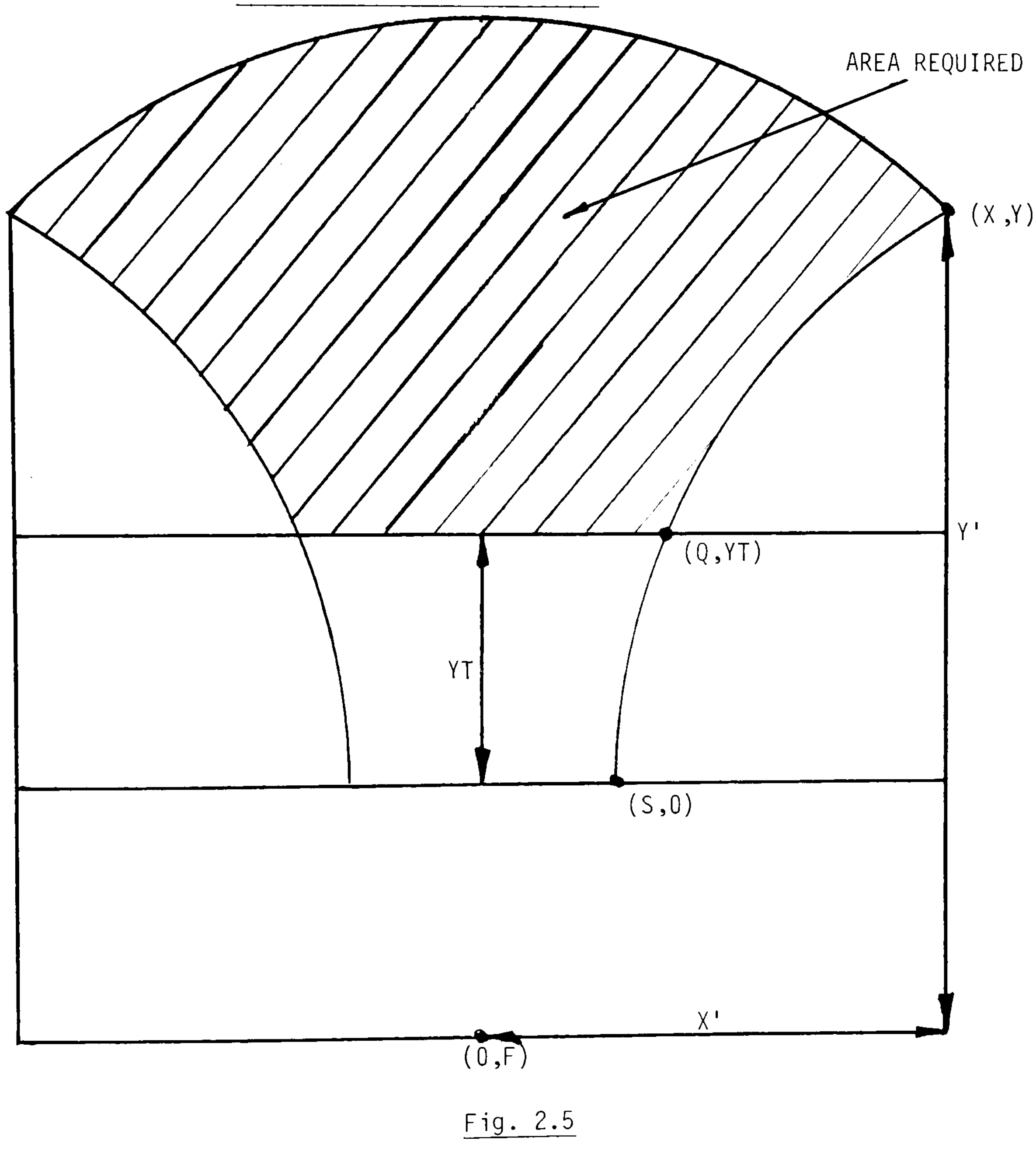
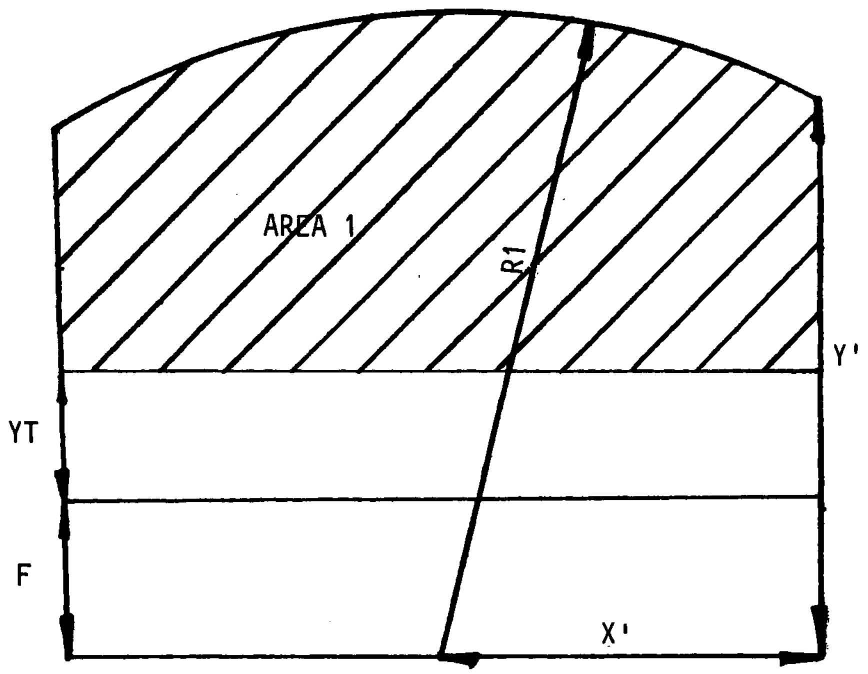


Fig. 2.5

ELEMENTS REQUIRED TO OBTAIN THE VOLUME OF THE COLLECTOR



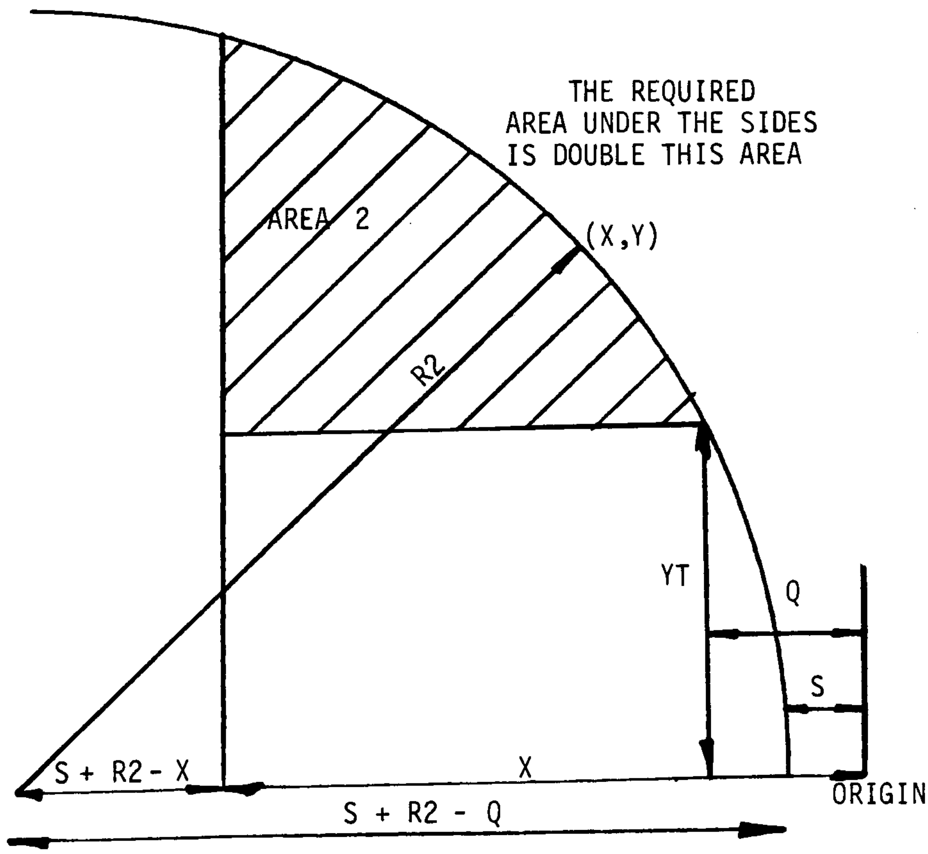


Fig 2.6

$$Y' = (R1^2 - X^2)^{0.5}$$

Also refering to Fig.2.6 the area below the receiver is 2X(F+YT) therefore AREA1, the area between the top surface the receiver and the intercept of the top and side surfaces, becomes:-

$$AREA1 = X(R1^2 - X^2)^{0.5} + \sin^{-1}(X/R1) - 2X(F+YT)$$

Consider the area under the side surfaces. The area under an arc can be used again but to enable the use of this equation a change of coordinates is required because the limits must be measured from the centre of curvature. Then from Fig.2.7 they are:-

the lower limit becomes S+R2-X

and the upper limit becomes S+R2-Q

The y coordinate can be replaced by:-

$$y = (R2^2 - x^2)^{0.5}$$

and since the area below the receiver is YT(X-Q), the required area AREA2 is the area given by [2.7] minus the area below the receiver and becomes:-

$$AREA2 = \left[x(R2^2 - x^2)^{0.5} + R2\sin^{-1}(x/R2)\right]_{S+R2-X}^{S+R2-Q} - 2YT(X-Q)$$

the composite volume is then:-

$$VOL = AREA1 - 2AREA2 \quad m^3 \text{ per metre length.}$$

In the simulation the subroutine VOLUME.FOR is used to evaluate the volume of any collector geometry whenever it is required.

2.3 THE OPTICAL EFFICIENCY SIMULATION DESIGN

2.3.1 PROGRAM DESIGN

The optical efficiency program can now be designed. For this Jacksons Structure Programming Diagrams {ref.2.1} will be used as these help with top down design and will modularise the required tasks to be undertaken. The following structure diagrams therefore contain all the requirements of the simulation as defined by the specification in section 2.2.1 and the elements show the correct order in which the various sections are programmed. Fig.2.7 demonstrates how the problem was gradually broken down into recognisable modules whereas the detailed structure digrams for the boundary surfaces shown in Fig.2.8 and the path evaluation in Fig.2.9 show how the modules were broken down into discrete procedures. These were then programmed using the definitions given throughout section 2.2. The suit of programs required for the simulation are listed below.

2.3.2 PROGRAMS FOR THE OPTICAL EFFICIENCY SIMULATION.

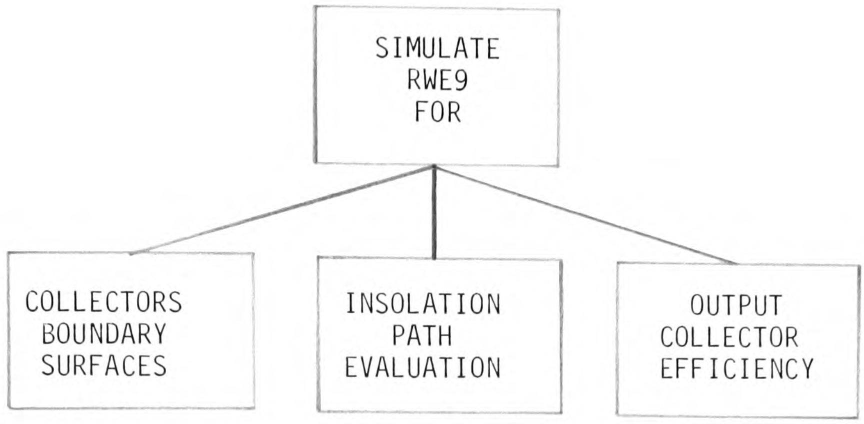
From the specifications, outline structures and mathematical formulations the following suit of programs have been written for the optical efficiency simulation.

RWE9.FOR	main program.
QUADRT.FOR	sub. for largest quad. soln.
QUADNG.FOR	sub. for smallest quad. soln.
RAYJ1.FOR	sub. for direction evaluation.
RAYJ2.FOR	sub. for direction evaluation.
EFFY.FOR	sub. to output results.
VOLUME.FOR	sub. for volume evaluation.

These programs contain detailed program decomposition and relate to the structure diagrams of section 2.3.1 and are listed in appendix A.

An extract from the resulting data file RWE9.DAT of 450 different shapes is shown in TABLE 2.1.

MODULES REQUIRED FOR THE OPTICAL EFFICIENCY SIMULATION



STRUCTURE DIAGRAM FOR THE OPTICAL EFFICIENCY SIMULATION

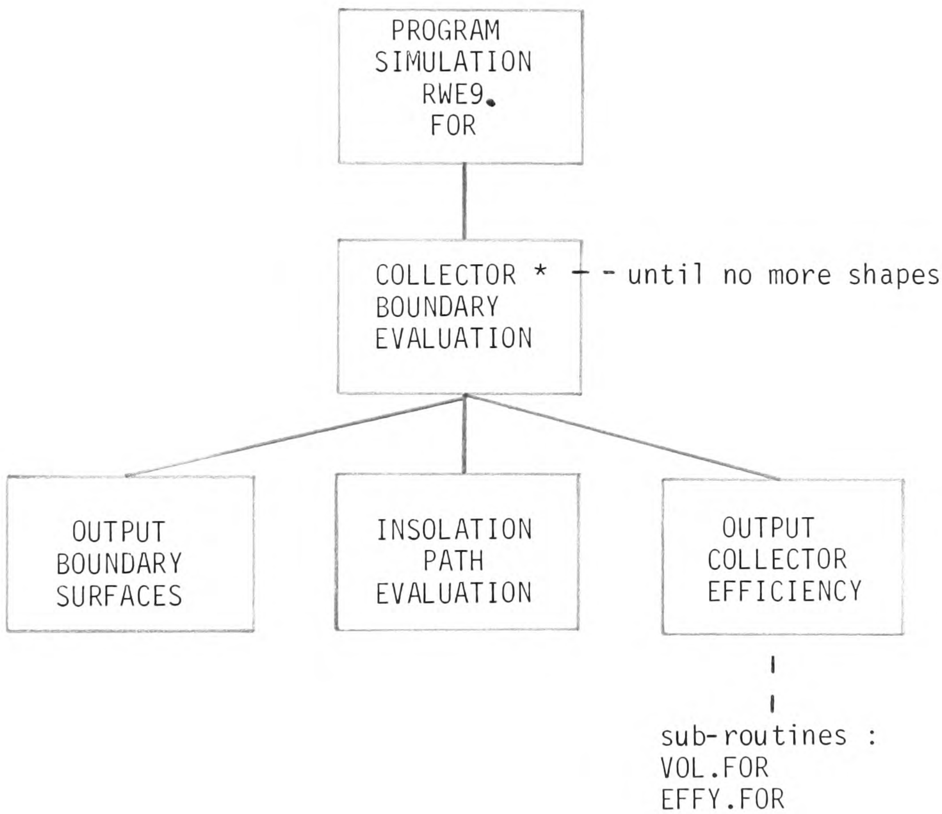


Fig. 2.7

THE STRUCTURE DIAGRAM FOR THE BOUNDARY SURFACES

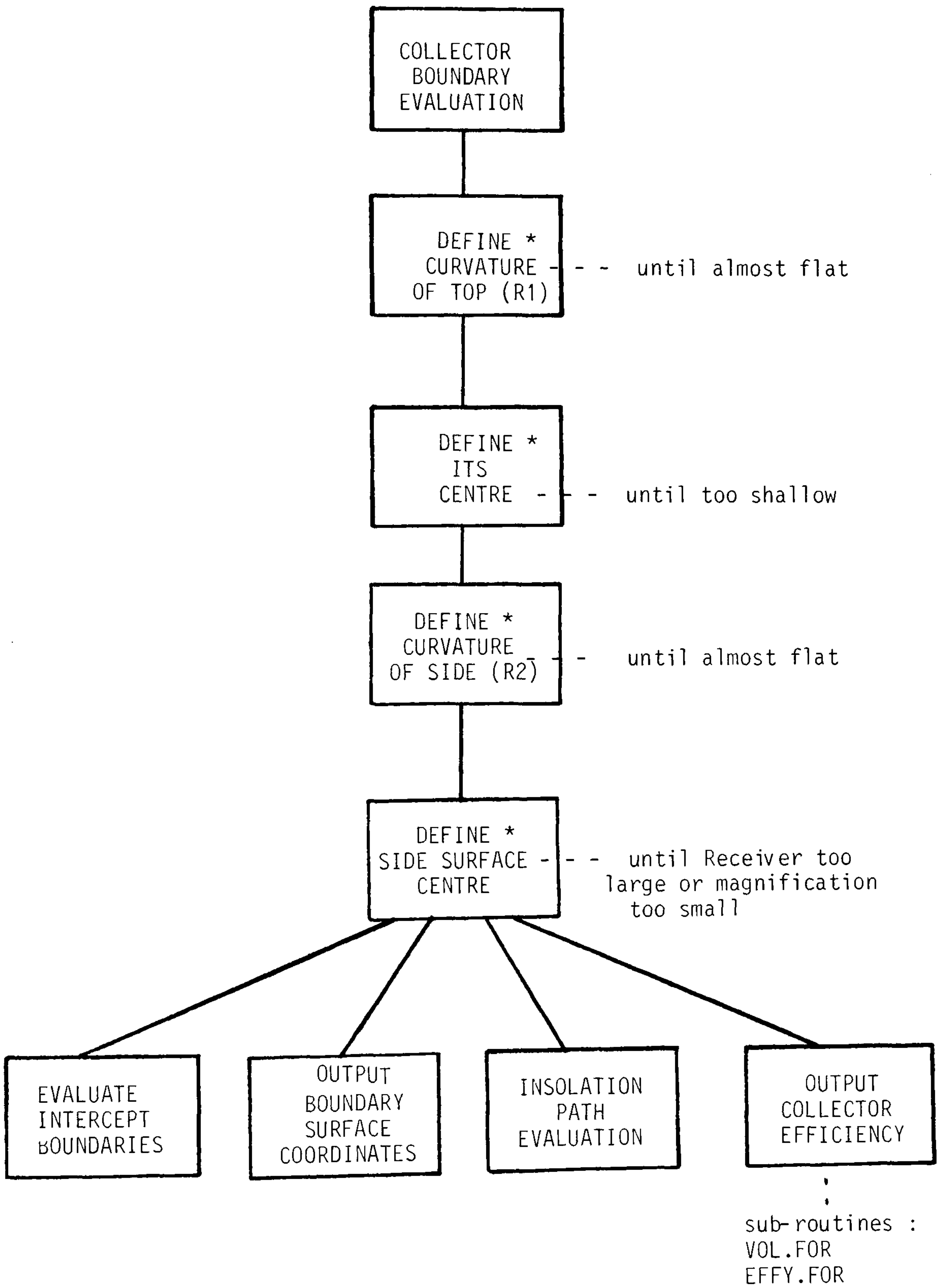
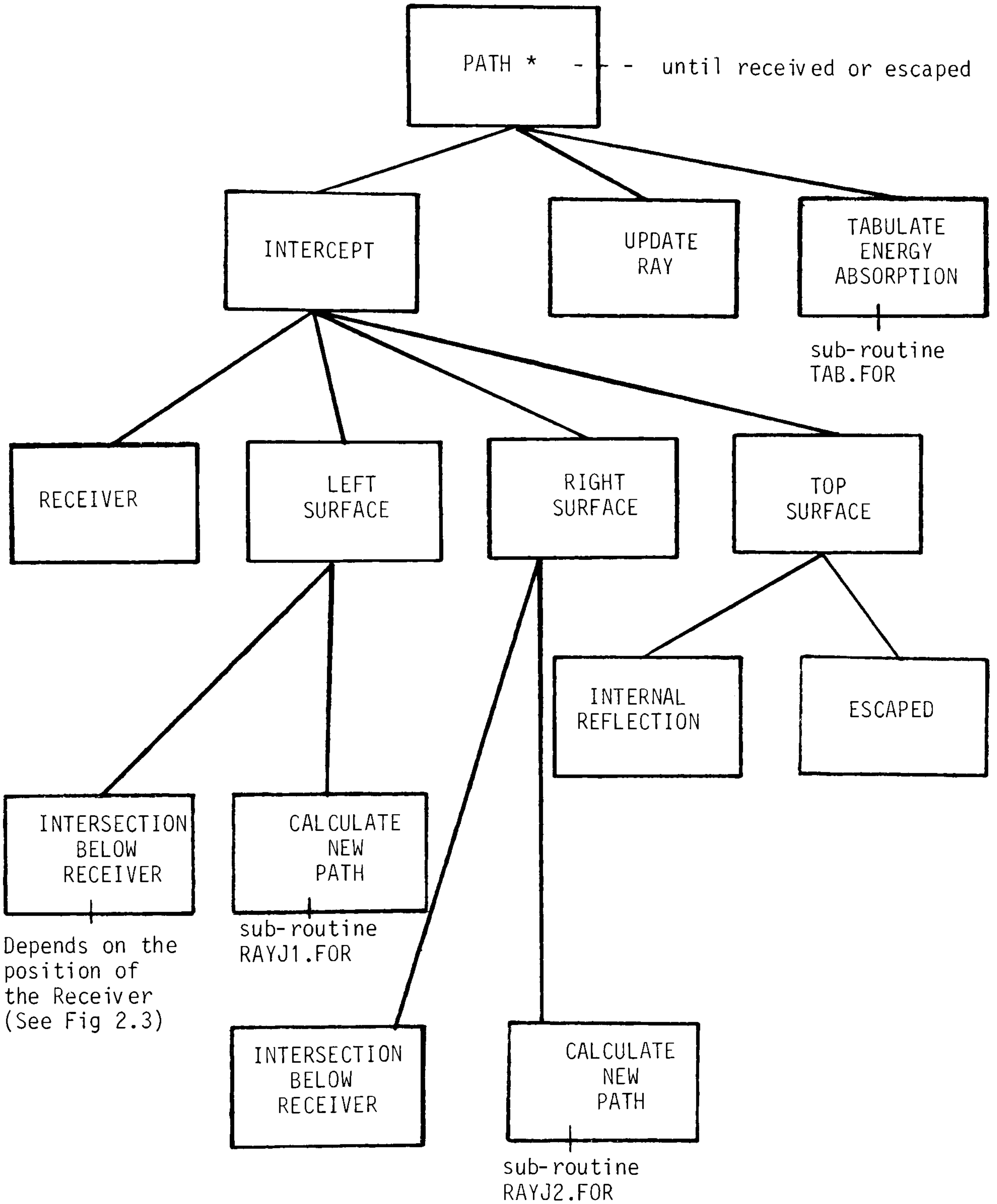


Fig. 2.8

THE STRUCTURE DIAGRAM FOR THE PATH OF RAY



TABULATED ENERGY ABSORPTION ONLY INCLUDED ON REVISED VERSION FOR HEAT LOSS SIMULATION. (Sub-routine TAB.FOR)

Fig 2.9

SIMULATED EFFICIENCIES FOR VARIOUS COLLECTOR GEOMETRIES

DATA FILE: RWE9.DAT

THE CENTRE OF THE TOP CURVED SURFACE IS (0 , 5.0).
THE CENTRE OF THE SIDE CURVED SURFACE ARE (-11.0 , 0) AND (11.0 , 0)
LENGTH OF RADIUS OF TOP SURFACE 10.
LENGTH OF RADIUS OF SIDE SURFACE 10.
COORDINATES OF CURVED SURFACE INTERSECTION
(-8.80 , 9.75) (8.80 , 9.75)

X COORDINATES OF THE SOLAR TRAP ARE BETWEEN 1.0 AND-1.0
THE VOLUME OF COLLECTOR PER UNIT LENGTH IS 123.95X10^-4 M^3
ROTS. COTS. ROSS. COLSS. .ANGLE OF INCIDENT RAY TO THE VERTICAL.

10.CMS(0,	5.)	10.CMS(11.,0)	30	25	20	15	10	5	0	5	10	15	20	25	30
% OF RAYS REACHING THE COLLECTOR			12.8	19.2	25.3	30.6	34.6	37.2	38.1	37.2	34.6	30.6	25.3	19.2	12.8
% OF ENERGY REACHING THE COLLECTOR			9.3	14.0	18.5	22.3	25.3	27.2	27.8	27.2	25.3	22.3	18.5	14.0	9.3
	40°C	WINTER.	6.2	10.9	15.4	19.2	22.2	24.1	24.8	24.1	22.2	19.2	15.4	10.9	6.2
L/V= 14.2	40°C	SUMMER.	8.8	13.5	17.9	21.8	24.8	26.6	27.3	26.6	24.8	21.8	17.9	13.5	8.8
	80°C	WINTER.	3.2	7.9	12.4	16.2	19.2	21.1	21.7	21.1	19.2	16.2	12.4	7.9	3.2
KQ=.076	80°C	SUMMER.	8.3	13.0	17.5	21.3	24.3	26.2	26.8	26.2	24.3	21.3	17.5	13.0	8.3

X COORDINATES OF THE SOLAR TRAP ARE BETWEEN 2.0 AND-2.0
THE VOLUME OF COLLECTOR PER UNIT LENGTH IS 112.38X10^-4 M^3
ROTS. COTS. ROSS. COLSS. .ANGLE OF INCIDENT RAY TO THE VERTICAL.

10.CMS(0,	5.)	10.CMS(11.,0)	30	25	20	15	10	5	0	5	10	15	20	25	30
% OF RAYS REACHING THE COLLECTOR			31.5	37.5	42.7	47.0	50.1	52.0	52.7	52.0	50.1	47.0	42.7	37.5	31.5
% OF ENERGY REACHING THE COLLECTOR			23.5	27.9	31.8	34.9	37.3	38.7	39.2	38.7	37.3	34.9	31.8	27.9	23.5
	40°C	WINTER.	14.9	19.3	23.2	26.4	28.8	30.2	30.7	30.2	28.8	26.4	23.2	19.3	14.9
L/V= 15.7	40°C	SUMMER.	22.0	26.5	30.3	33.5	35.9	37.3	37.8	37.3	35.9	33.5	30.3	26.5	22.0
	80°C	WINTER.	6.4	10.8	14.7	17.9	20.2	21.7	22.1	21.7	20.2	17.9	14.7	10.8	6.4
KQ=.214	80°C	SUMMER.	20.7	25.1	29.0	32.2	34.5	36.0	36.4	36.0	34.5	32.2	29.0	25.1	20.7

X COORDINATES OF THE SOLAR TRAP ARE BETWEEN 3.0 AND-3.0
THE VOLUME OF COLLECTOR PER UNIT LENGTH IS 104.30X10^-4 M^3
ROTS. COTS. ROSS. COLSS. .ANGLE OF INCIDENT RAY TO THE VERTICAL.

10.CMS(0,	5.)	10.CMS(11.,0)	30	25	20	15	10	5	0	5	10	15	20	25	30
% OF RAYS REACHING THE COLLECTOR			43.3	47.6	52.6	56.6	59.5	61.2	61.7	61.2	59.5	56.6	52.6	47.6	43.3
% OF ENERGY REACHING THE COLLECTOR			32.5	35.8	39.5	42.5	44.7	46.1	46.5	46.1	44.7	42.5	39.5	35.8	32.5
	40°C	WINTER.	17.4	20.6	24.4	27.4	29.6	30.9	31.3	30.9	29.6	27.4	24.4	20.6	17.4
L/V= 16.9	40°C	SUMMER.	30.0	33.2	37.0	40.0	42.2	43.5	43.9	43.5	42.2	40.0	37.0	33.2	30.0
	80°C	WINTER.	2.2	5.4	9.2	12.2	14.4	15.7	16.1	15.7	14.4	12.2	9.2	5.4	2.2
KQ=.379	80°C	SUMMER.	27.6	30.8	34.6	37.6	39.8	41.1	41.5	41.1	39.8	37.6	34.6	30.8	27.6

X COORDINATES OF THE SOLAR TRAP ARE BETWEEN 4.0 AND-4.0
THE VOLUME OF COLLECTOR PER UNIT LENGTH IS 96.37X10^-4 M^3
ROTS. COTS. ROSS. COLSS. .ANGLE OF INCIDENT RAY TO THE VERTICAL.

10.CMS(0,	5.)	10.CMS(11.,0)	30	25	20	15	10	5	0	5	10	15	20	25	30
% OF RAYS REACHING THE COLLECTOR			57.4	59.9	61.9	63.2	65.1	66.7	67.1	66.7	65.1	63.2	61.9	59.9	57.4
% OF ENERGY REACHING THE COLLECTOR			43.6	45.4	46.9	48.0	49.4	50.6	51.0	50.6	49.4	48.0	46.9	45.4	43.6
	40°C	WINTER.	20.4	22.3	23.8	24.8	26.2	27.5	27.9	27.5	26.2	24.8	23.8	22.3	20.4
L/V= 18.3	40°C	SUMMER.	39.7	41.5	43.1	44.1	45.5	46.8	47.1	46.8	45.5	44.1	43.1	41.5	39.7
	80°C	WINTER.	-2.7	-0.9	0.6	1.7	3.1	4.4	4.7	4.4	3.1	1.7	0.6	-0.9	-2.7
KQ=.579	80°C	SUMMER.	36.0	37.9	39.4	40.4	41.9	43.1	43.5	43.1	41.9	40.4	39.4	37.9	36.0

TABLE 2.1

2.4 THE OPTIMUM COLLECTOR SHAPE CHOICE

There are many factors which govern the choice of the optimum concentrating collector. As efficiency is partly dependant on heat loss and weather conditions it was first decided that the operating climatic conditions of interest in this study would be those normal for the British Isles. It was further envisaged that a reduction in maximum efficiency could be tollerated if the collector could more than make up for this by working all the year round, especially when the temperature differentials are not as favourable and other types of collector are inactive. Another criteria that was used in this optimisation was that the collector should not be very directionally dependant and therefore the collector would require good performance over the full 60^{o} range of incident radiation considered in the simulation.
Magnification is a very important parameter within the optimisation choice because it effects several different aspects of the collector. As can be seen from the results, collectors with higher magnification are more directionally dependant. It is also true that collectors with higher magnifications tend to be capable of greater working temperature differentials and able to work in lower insolation intensities.

The elementary heat loss analysis undertaken in section 2.2.4 assumes that the heat loss would be the same for any collector with the same depth to receiver width ratio, this is not generally the case and is normally a function of magnification. In general the higher the magnification the greater the stagnation temperature and lower the time constant, this however is not inherently apparent from the simulation because the efficiencies have been estimated for known working temperatures, and any advantages to be gained from smaller thermal masses have so far been neglected. The thermal mass of the collectors should therefore be taken into considered in the final optimisation.

An indication of the heat loss for each shape can be gained from the heat loss coefficient KQ, the slope of the efficiency (n%) against DT/E graph and is used in the optimisation to predict the root or intercept (n/KQ) on the DT/E axis. It is this value together with the maximum efficiency that gives the best indication of how well the collector will perform in the steady state condition.

An approximation of cost per unit incident energy for each collector can be obtained from the collector parameter L/V (surface area to volume per unit length) and this with collector efficiencies for different weather conditions gives an estimate of the cost per unit energy gain.

Approximately 450 different shapes have been evaluated and from these a short list of the best collector's parameters have been profiled in TABLE 2.2. From these one has been chosen for further analysis.

The most promising geometries were determined by maximising the "maximum efficiency by the heat loss coefficient" for the case of normal incident radiation $n_m(0^o)/KQ$. This parameter which is the theoretical stagnation temperature per unit intensity DT/E together with the maximum efficiency provided a short list of the better collectors. From this test it can be seen that the four best collectors (*) all have magnifications in the region of 3 and L/V values of about 12. Of these the collector with the flat top surface was chosen because of its simple geometry.

The collector chosen for further investigation and verification of results has been underlined. Its full definition and efficiencies are shown in TABLE 2.3

A PROFILE OF COLLECTOR PARAMETERS

MAG.	L/V	EFFY n_m%		KQ.	$n_m(0^o)$/KQ	R1	R2
	m^{-2}	15^o	0^o	$Wm^{-2}C^{-1}$	$C(Wm^{-2})^{-1}$	m	m
2.1	10.3	73	73	0.316	0.231	10	26
2.2	13.1	72	74	0.377	0.196	10	26
2.9	12.7	55	58	0.249	0.233	30	26
2.6	13.1	60	63	0.294	0.214	30	26
3.4	17.2	55	59	0.271	0.218	30	26
2.2	14.2	68	74	0.423	0.175	30	26
*2.9	11.9	65	73	0.227	0.322	30	58
2.5	12.7	73	74	0.314	0.236	30	58
2.2	13.2	74	74	0.372	0.199	30	58
2.0	13.8	74	74	0.446	0.166	30	58
3.9	16.6	46	50	0.215	0.233	70	26
2.5	12.8	73	74	0.312	0.238	70	58
4.5	16.1	39	43	0.173	0.249	150	26
3.4	17.3	52	56	0.266	0.211	150	26
*3.0	12.0	62	73	0.225	0.324	150	58
*3.0	12.0	62	73	0.224	0.326	1250	58
2.6	18.9	63	73	0.426	0.171	2550	26
*3.0	12.0	62	73	0.224	0.326	2550	58

Where n_m% is the maximum efficiency (when DT/E=0) for the solar beam with incident angles for normal radiation (0^o) and for off normal radiation of 15^o.

TABLE 2.2

THE SIMULATED EFFICIENCIES AND GEOMETRIC DEFINITION OF THE CHOSEN COLLECTOR

DATA FILE: RWE9.DAT

THE CENTRE OF THE TOP CURVED SURFACE IS (0 ,-2535.0).
THE CENTRE OF THE SIDE CURVED SURFACE ARE (-59.0 , 0) AND (59.0 , 0)
LENGTH OF RADIUS OF TOP SURFACE 2550.
LENGTH OF RADIUS OF SIDE SURFACE 58.
COORDINATES OF CURVED SURFACE INTERSECTION
(-2.97 , 15.00) (2.97 , 15.00)

X COORDINATES OF THE SOLAR TRAP ARE BETWEEN 1.0 AND-1.0
THE VOLUME OF COLLECTOR PER UNIT LENGTH IS 49.59X10^-4 M^3

ROTS.	COTS.	ROSS. COLSS.	.ANGLE OF INCIDENT RAY TO THE VERTICAL.												
2550.CMS(0, -2535.)		58.CMS(59.,0)	30	25	20	15	10	5	0	5	10	15	20	25	30
% OF RAYS REACHING THE COLLECTOR			56.7	66.9	76.4	84.9	92.4	98.8	100.0	98.8	92.4	84.9	76.4	66.9	56.7
% OF ENERGY REACHING THE COLLECTOR			41.0	48.4	55.4	61.7	67.2	71.9	72.8	71.9	67.2	61.7	55.4	48.4	41.0
	40°C	WINTER.	32.0	39.5	46.4	52.7	58.2	62.9	63.8	62.9	58.2	52.7	46.4	39.5	32.0
L/V= 12.0	40°C	SUMMER.	39.5	46.9	53.9	60.2	65.7	70.4	71.3	70.4	65.7	60.2	53.9	46.9	39.5
	80°C	WINTER.	23.0	30.5	37.5	43.7	49.2	53.9	54.9	53.9	49.2	43.7	37.5	30.5	23.0
KQ=.224	80°C	SUMMER.	38.0	45.5	52.5	58.8	64.2	69.0	69.9	69.0	64.2	58.8	52.5	45.5	38.0

TABLE 2.3

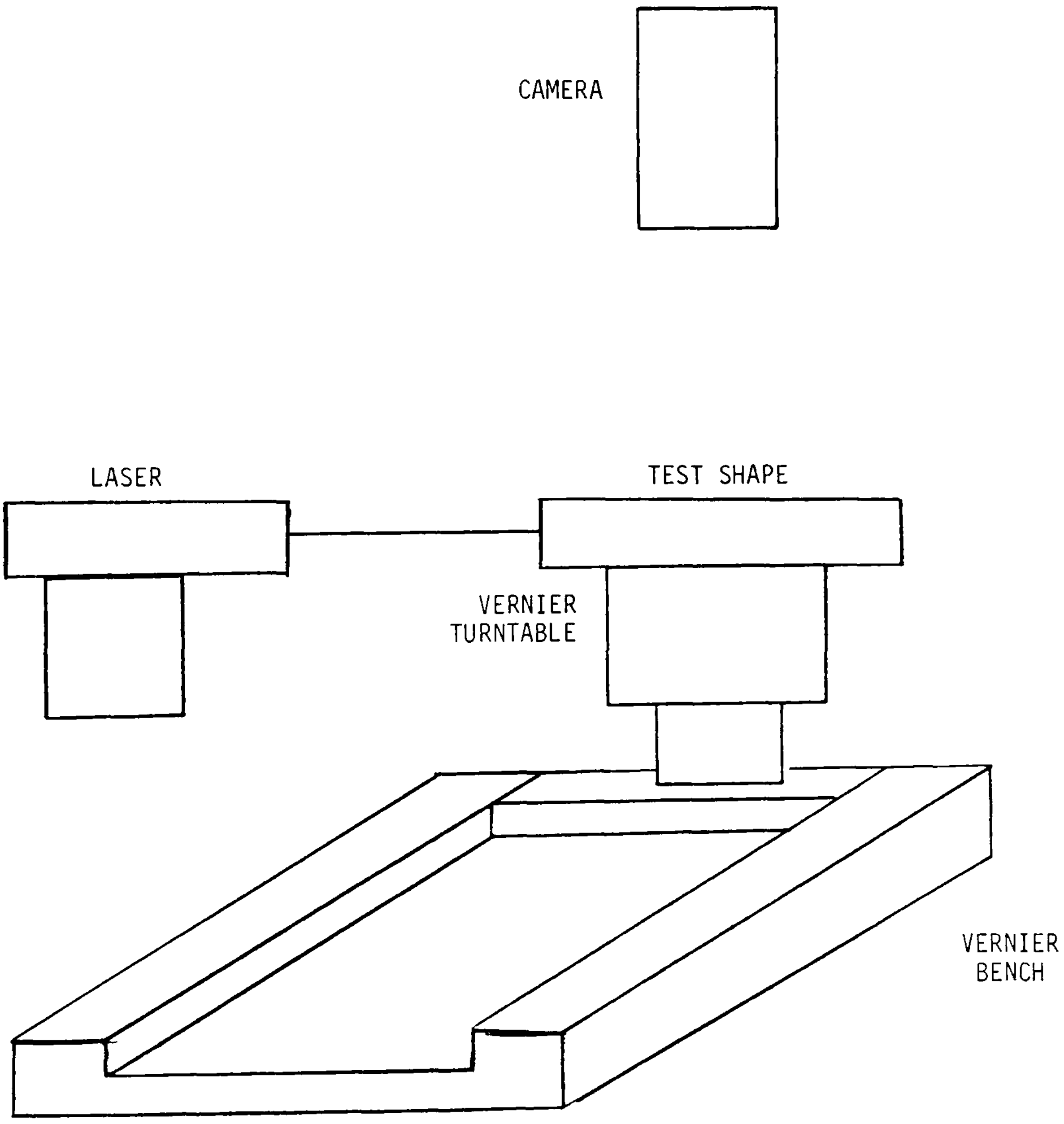
2.5 EXPERIMENTAL RAY TRACKING VERIFICATION

2.5.1 EXPERIMENTAL PROCEDURE

Once the choice of collector shape had been made (as shown at the top of Fig.2.12) it was necessary to verify the computed ray tracking simulation with the aid of a ray tracking experiment. For this comparison a new table of results, produced by the simulation, itemises the path of each ray as it passes through the collector. Extracts of which are shown in TABLES 2.4-2.6. These tables consist of the geometric definition of the collector and the angle of incident solar radiation under consideration. The table then shows a profile of each ray that passes through the collector. This profile consists of the X-coordinate of the incoming ray on the top surface with its corresponding vernier reading equivalent (see section 2.5.2), the number of side reflections, the number of total internal reflections on the top surface, the path length of the ray and if it reaches the receiver its intercept coordinate. These results have clearly shown the limiting coordinate positions of those rays that reach the collector.

An experiment was then carried out to verify these limiting values. The apparatus as shown in Fig.2.10 and Fig.2.11 consisted of a perspex slab cut and polished to the correct shape with its side surfaces aluminised. A lazer was then used to produce rays of light at various angles of incidence. The angle of the incident radiation could be found directly from the turntable vernier but the x-coordinate position of the incident ray was calculated from both the vernier turntable and the bench vernier readings. A subroutine included in the simulation converts the x coordinate positions into the experimental vernier reading equivalents.

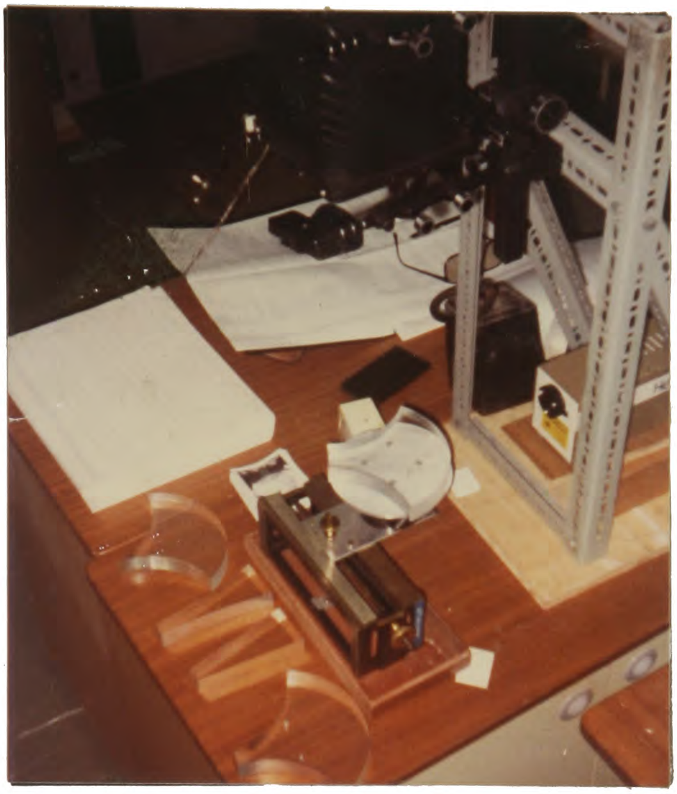
It was possible with this experiment to reproduce any of the predicted ray tracks used in the simulation. Photos of the lazer's path, as it passed through the slab have been taken and are shown in TABLES 2.5 and 2.6. These demonstrate the limiting coordinate positions of rays reaching the receiver.



BLOCK DIAGRAM OF THE RAY TRACKING EXPERIMENT

Fig 2.10

THE EXPERIMENTAL RAY TRACKING APPARATUS



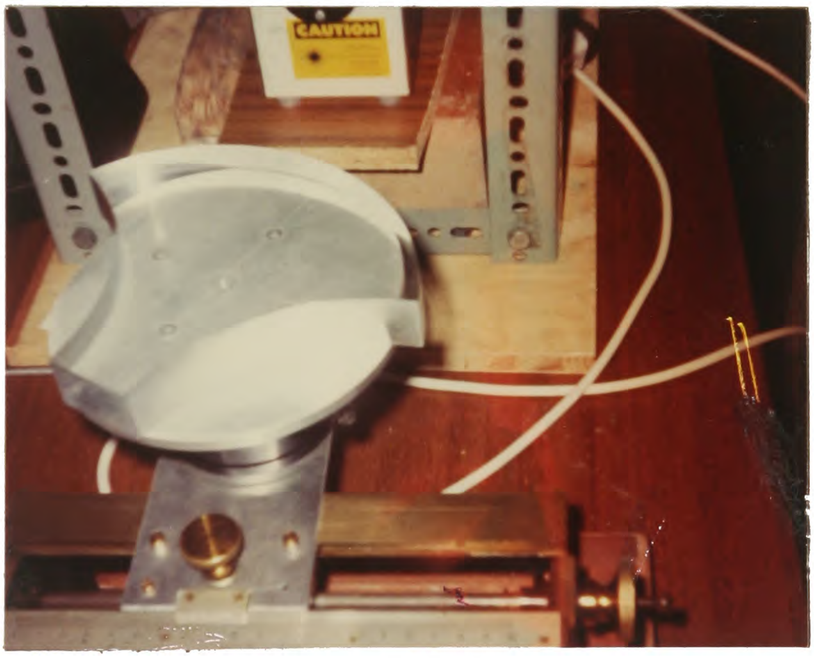


Fig. 2.11

A PROFILE OF EACH RAY AS IT PASSES THROUGH THE CHOSEN COLLECTOR

```
*********************************
*      DATA FILE: REW92.DAT     *
*********************************
```

THE CENTRE OF THE TOP CURVED SURFACE IS (0 ,-2535.0).
THE CENTRE OF THE SIDE CURVED SURFACE ARE (-59.0 , 0) AND (59.0 , 0)
LENGTH OF RADIUS OF TOP SURFACE 2550.
LENGTH OF RADIUS OF SIDE SURFACE 58.
COORDINATES OF CURVED SURFACE INTERSECTION
(-2.97 , 15.00) (2.97 , 15.00)
ANGLE OF RAY——————————LQ.
X COORDINATE OF INCOMING RAY——————C.O.R.
NUMBER OF SIDE REFLECTIONS——————N.O.S.R.
NUMBER OF TIMES BEAM TOTALLY INTERNALLY
REFLECTED ON TOP SURFACE——————T.I.R.
INTENSITY AS A PERCENTAGE OF INCIDENT RAYS —INTENSITY.

X COORDINATES OF THE SOLAR TRAP ARE BETWEEN 1.0 AND-1.0
THE VOLUME OF COLLECTOR PER UNIT LENGTH IS 49.59X10^-4 M^3
INCIDENT ANGLE INDEGREES. 240

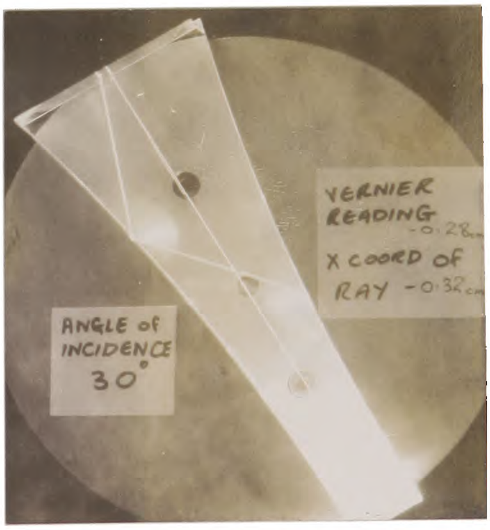
VERNIER.	C.O.R.	N.O.S.R.	T.I.R.	LEN. PATH.	RAY.ESC. OR X COORD OF COLLECTOR
-2.424	-2.80	6.0	0.0	25.80	ESCAPED.
-2.415	-2.79	6.0	0.0	25.85	ESCAPED.
-2.407	-2.78	6.0	0.0	25.89	ESCAPED.
-2.398	-2.77	6.0	0.0	25.94	ESCAPED.
-2.389	-2.76	6.0	0.0	25.98	ESCAPED.
-2.381	-2.75	6.0	0.0	26.03	ESCAPED.
-2.372	-2.74	6.0	0.0	26.08	ESCAPED.
-2.364	-2.73	6.0	0.0	26.13	ESCAPED.
-2.355	-2.72	6.0	0.0	26.18	ESCAPED.
-2.346	-2.71	6.0	0.0	26.23	ESCAPED.
-2.338	-2.70	6.0	0.0	26.28	ESCAPED.
-2.329	-2.69	6.0	0.0	26.34	ESCAPED.
-2.320	-2.68	6.0	0.0	26.39	ESCAPED.
-2.312	-2.67	6.0	0.0	26.45	ESCAPED.
-2.303	-2.66	6.0	0.0	26.50	ESCAPED.
-2.294	-2.65	6.0	0.0	26.56	ESCAPED.
-2.286	-2.64	6.0	0.0	26.62	ESCAPED.
-2.277	-2.63	6.0	0.0	26.67	ESCAPED.
-2.268	-2.62	6.0	0.0	26.73	ESCAPED.
-2.260	-2.61	6.0	0.0	26.79	ESCAPED.
-2.251	-2.60	6.0	0.0	26.85	ESCAPED.
-2.242	-2.59	6.0	0.0	26.92	ESCAPED.
-2.234	-2.58	6.0	0.0	26.98	ESCAPED.
-2.225	-2.57	6.0	0.0	27.04	ESCAPED.
-2.216	-2.56	6.0	0.0	27.11	ESCAPED.
-2.208	-2.55	6.0	0.0	27.18	ESCAPED.
-2.199	-2.54	6.0	0.0	27.24	ESCAPED.
-2.190	-2.53	6.0	0.0	27.31	ESCAPED.
-2.182	-2.52	10.0	1.0	45.46	ESCAPED.
-2.173	-2.51	10.0	1.0	45.19	ESCAPED.
-2.164	-2.50	10.0	1.0	44.95	ESCAPED.
-2.156	-2.49	29.0	8.0	143.98	ESCAPED.
-2.147	-2.48	20.0	4.0	95.20	ESCAPED.
-2.138	-2.47	23.0	7.0	116.50	ESCAPED.
-2.130	-2.46	30.0	11.0	155.27	ESCAPED.
-2.121	-2.45	35.0	10.0	175.08	ESCAPED.
-2.112	-2.44	17.0	3.0	81.96	ESCAPED.

TABLE 2.4

```
**********************************
*       DATA FILE: REW92.DAT     *
**********************************
```

INCIDENT ANGLE INDEGREES. 240

VERNIER.	C.O.R.	N.O.S.R.	T.I.R.	LEN. PATH.	RAY.ESC. OR X COORD OF COLLECTOR
-0.450	-0.52	16.0	0.0	52.22	ESCAPED.
-0.442	-0.51	17.0	0.0	52.63	ESCAPED.
-0.433	-0.50	17.0	0.0	53.28	ESCAPED.
-0.424	-0.49	17.0	0.0	54.33	ESCAPED.
-0.416	-0.48	18.0	0.0	54.88	ESCAPED.
-0.407	-0.47	18.0	0.0	55.99	ESCAPED.
-0.398	-0.46	19.0	0.0	56.91	ESCAPED.
-0.390	-0.45	19.0	0.0	58.48	ESCAPED.
-0.381	-0.44	20.0	0.0	59.73	ESCAPED.
-0.372	-0.43	21.0	0.0	61.54	ESCAPED.
-0.364	-0.42	22.0	0.0	64.15	ESCAPED.
-0.355	-0.41	24.0	0.0	67.64	ESCAPED.
-0.346	-0.40	28.0	0.0	74.81	ESCAPED.
-0.338	-0.39	14.0	0.0	38.74	-0.9999
-0.329	-0.38	12.0	0.0	34.69	-0.9380
-0.320	-0.37	11.0	0.0	32.58	0.8151
-0.312	-0.36	10.0	0.0	30.78	-0.9999
-0.303	-0.35	10.0	0.0	30.24	-0.4482
-0.294	-0.34	9.0	0.0	28.82	0.9999
-0.286	-0.33	9.0	0.0	28.80	0.9861
-0.277	-0.32	9.0	0.0	28.25	0.4218
-0.268	-0.31	9.0	0.0	27.77	-0.0753
-0.260	-0.30	8.0	0.0	26.87	-0.9999
-0.251	-0.29	8.0	0.0	26.87	-0.9999
-0.242	-0.28	8.0	0.0	26.61	-0.7330
-0.234	-0.27	8.0	0.0	26.29	-0.4034
-0.225	-0.26	8.0	0.0	26.00	-0.0976
-0.217	-0.25	8.0	0.0	25.73	0.1868
-0.208	-0.24	8.0	0.0	25.48	0.4520
-0.199	-0.23	7.0	0.0	24.95	0.9999
-0.191	-0.22	7.0	0.0	24.96	0.9999
-0.182	-0.21	7.0	0.0	24.82	0.8496
-0.173	-0.20	7.0	0.0	24.62	0.6411
-0.165	-0.19	7.0	0.0	24.43	0.4420
-0.156	-0.18	7.0	0.0	24.26	0.2516
-0.147	-0.17	7.0	0.0	24.09	0.0693
-0.139	-0.16	7.0	0.0	23.92	-0.1053
-0.130	-0.15	7.0	0.0	23.77	-0.2727
-0.121	-0.14	7.0	0.0	23.62	-0.4333
-0.113	-0.13	7.0	0.0	23.48	-0.5875
-0.104	-0.12	6.0	0.0	23.10	-0.9999
-0.095	-0.11	6.0	0.0	23.10	-0.9999
-0.087	-0.10	6.0	0.0	23.09	-0.9847
-0.078	-0.09	6.0	0.0	22.97	-0.8518
-0.069	-0.08	6.0	0.0	22.85	-0.7227
-0.061	-0.07	6.0	0.0	22.74	-0.5970
-0.052	-0.06	6.0	0.0	22.63	-0.4746
-0.043	-0.05	6.0	0.0	22.52	-0.3554
-0.035	-0.04	6.0	0.0	22.42	-0.2394
-0.026	-0.03	6.0	0.0	22.32	-0.1263
-0.017	-0.02	6.0	0.0	22.22	-0.0162
-0.009	-0.01	6.0	0.0	22.13	0.0912
0.000	0.00	6.0	0.0	22.03	0.1960



THE PHOTO DEMONSTRATES THE PATH OF THE RAY UNDERLINED.

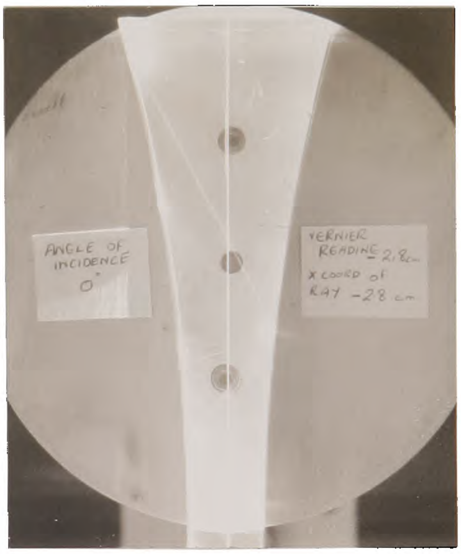
TABLE 2.5

ANOTHER EXTRACT FROM THE PROFILE TABLE OF THE CHOSEN COLLECTOR

```
**********************************
*       DATA FILE: REW92.DAT     *
**********************************
```

INCIDENT ANGLE INDEGREES. 270

VERNIER.	C.O.R.	N.O.S.R.	T.I.R.	LEN. PATH.	RAY.ESC. OR X COORD OF COLLECTOR
-2.940	-2.94	6.0	0.0	21.36	0.3292
-2.930	-2.93	6.0	0.0	21.21	0.5056
-2.920	-2.92	6.0	0.0	21.06	0.6746
-2.910	-2.91	5.0	0.0	20.78	0.9999
-2.900	-2.90	5.0	0.0	20.78	0.9999
-2.890	-2.89	5.0	0.0	20.65	0.8571
-2.880	-2.88	5.0	0.0	20.53	0.7109
-2.870	-2.87	5.0	0.0	20.41	0.5687
-2.860	-2.86	5.0	0.0	20.29	0.4303
-2.850	-2.85	5.0	0.0	20.18	0.2956
-2.840	-2.84	5.0	0.0	20.07	0.1644
-2.830	-2.83	5.0	0.0	19.96	0.0368
-2.820	-2.82	5.0	0.0	19.86	-0.0876
-2.810	-2.81	5.0	0.0	19.76	-0.2087
-2.800	-2.80	5.0	0.0	19.67	-0.3267
-2.790	-2.79	5.0	0.0	19.57	-0.4417
-2.780	-2.78	5.0	0.0	19.48	-0.5537
-2.770	-2.77	5.0	0.0	19.40	-0.6629
-2.760	-2.76	5.0	0.0	19.31	-0.7693
-2.750	-2.75	4.0	0.0	19.13	-0.9999
-2.740	-2.74	4.0	0.0	19.13	-0.9999
-2.730	-2.73	4.0	0.0	19.07	-0.9269
-2.720	-2.72	4.0	0.0	19.00	-0.8297
-2.710	-2.71	4.0	0.0	18.92	-0.7341
-2.700	-2.70	4.0	0.0	18.85	-0.6399
-2.690	-2.69	4.0	0.0	18.78	-0.5473
-2.680	-2.68	4.0	0.0	18.71	-0.4562
-2.670	-2.67	4.0	0.0	18.65	-0.3665
-2.660	-2.66	4.0	0.0	18.58	-0.2783
-2.650	-2.65	4.0	0.0	18.52	-0.1915
-2.640	-2.64	4.0	0.0	18.45	-0.1060
-2.630	-2.63	4.0	0.0	18.39	-0.0219
-2.620	-2.62	4.0	0.0	18.33	0.0609
-2.610	-2.61	4.0	0.0	18.27	0.1423
-2.600	-2.60	4.0	0.0	18.21	0.2225
-2.590	-2.59	4.0	0.0	18.16	0.3014
-2.580	-2.58	4.0	0.0	18.10	0.3790
-2.570	-2.57	4.0	0.0	18.05	0.4554
-2.560	-2.56	4.0	0.0	18.00	0.5306
-2.550	-2.55	4.0	0.0	17.94	0.6045
-2.540	-2.54	4.0	0.0	17.89	0.6773
-2.530	-2.53	4.0	0.0	17.85	0.7489
-2.520	-2.52	4.0	0.0	17.80	0.8193
-2.510	-2.51	4.0	0.0	17.75	0.8885
-2.500	-2.50	3.0	0.0	17.68	0.9999



THE PHOTO DEMONSTRATES THE PATH OF THE RAY UNDERLINED.

TABLE 2.6

PHOTOGRAPHS OF LASER BEAM PASSING THROUGH VARIOUS PERSPEX SHAPES SHOWING LIMITING VIEWS OF LIGHT REACHING THE RECEIVER

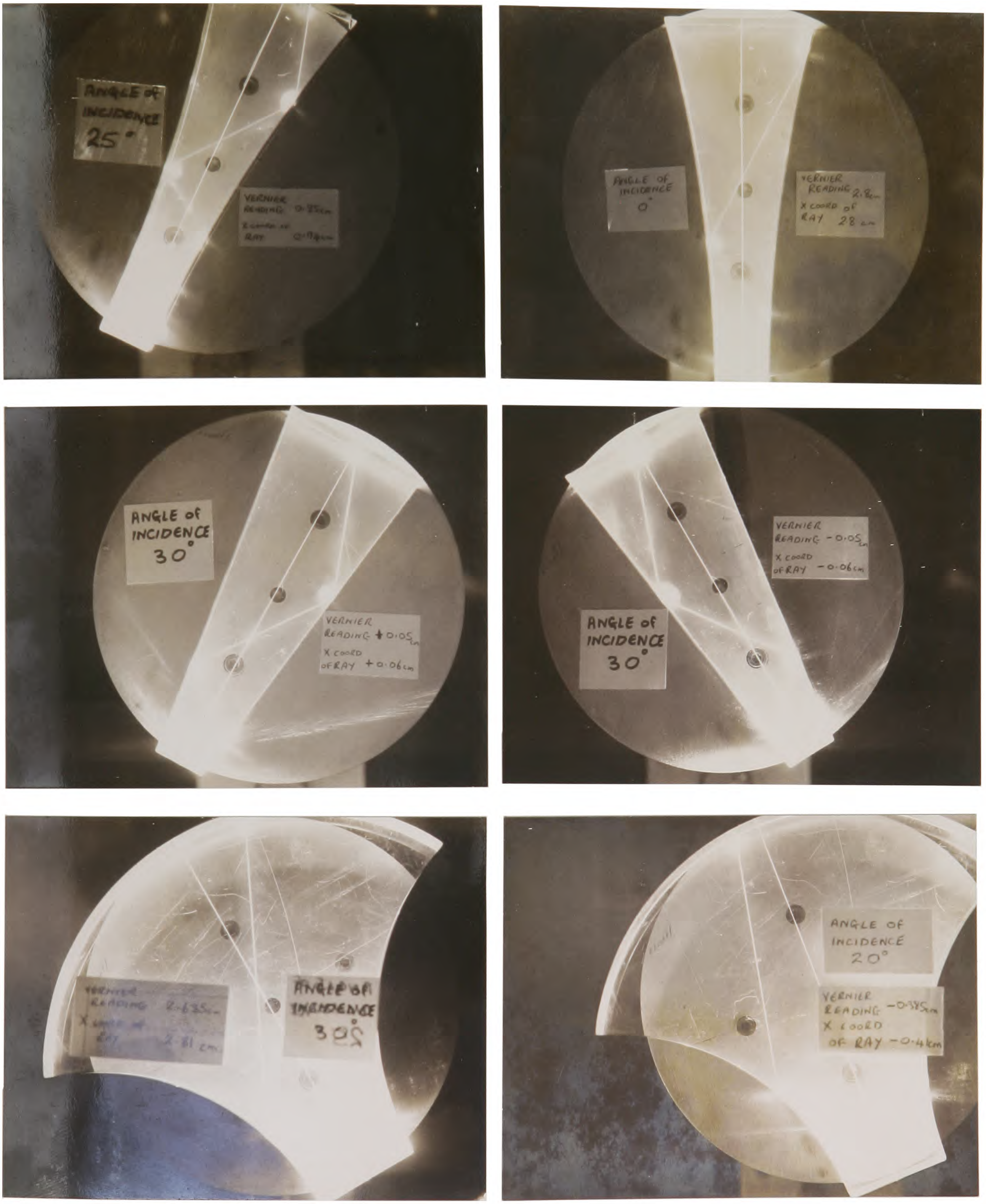


Fig 2.12

The experiment was repeated for another less efficient shape and the predicted limiting values were likewise correct. This less efficient shape is shown at the bottom of Fig.2.12.

The results from this experiment and those from the ray tracking simulation are consistent for both the chosen collector and the other less efficient shape. It therefore seems reasonable to assume that the simulated results are all correct.

2.5.2 SPECIFICATION FOR VERN.FOR

The routine required to determine the lateral vernier reading of the ray tracking experiment was based on the following consideration

From Fig.2.13 it follows that where X is the lateral displacement between the rays top surface intercept and the collectors normal axis and Y' the vertical displacement from its vertex.

$$X = Y'\sin Q + V/\cos Q$$

From the intersection of two chords in a circle of radius R

we have:-

$$Y'(2R-Y') = X^2$$

$$Y'^2 - 2RY' + X^2 = 0$$

From these two relationships V the lateral vernier reading can be obtained for each ray considered.

THE RELATIONSHIP BETWEEN THE VERNIER READING AND THE LATERAL DISPLACEMENT

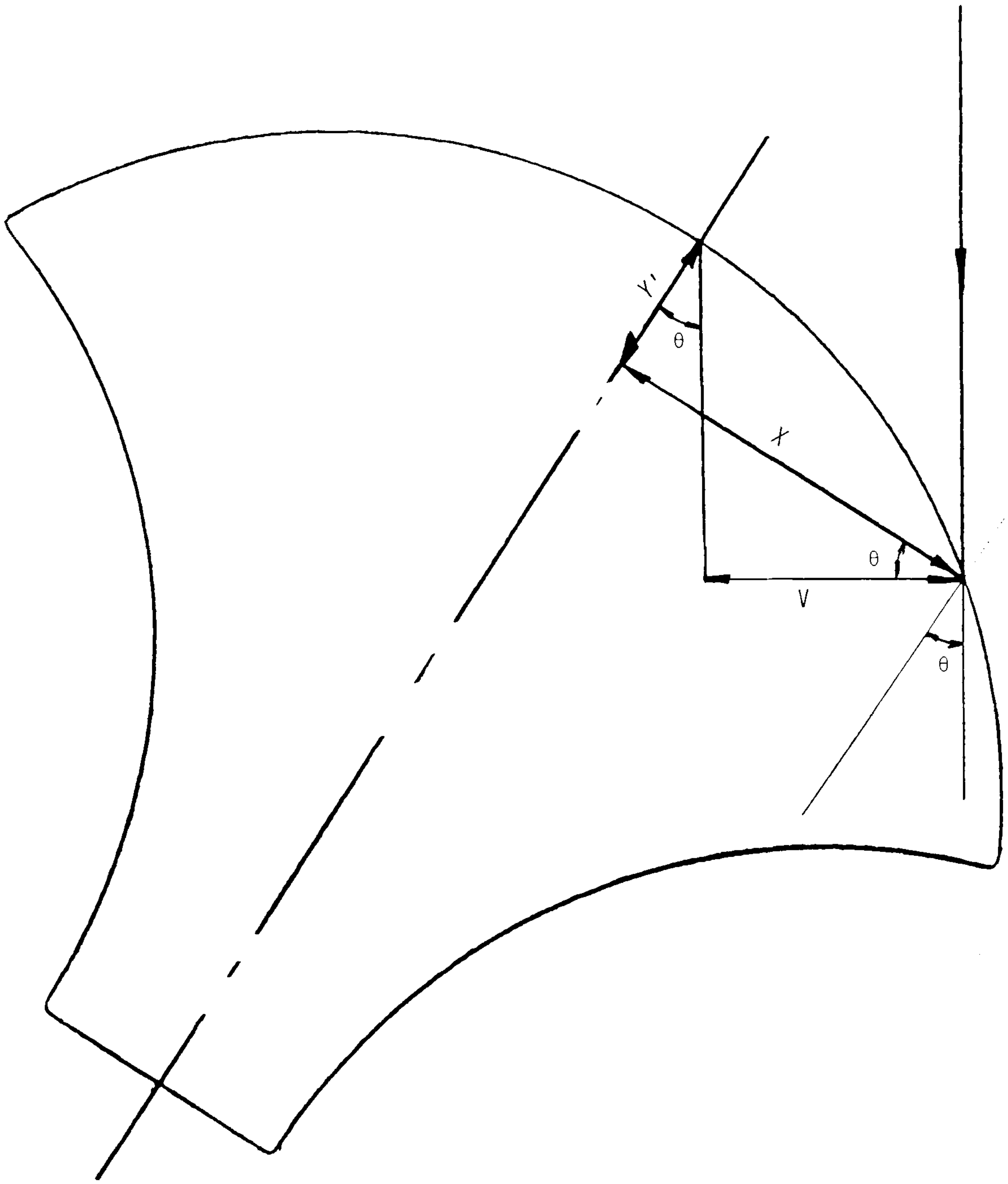


Fig 2.13

2.5.3 PROGRAMS FOR THE RAY TRACKING VERIFICATION

The new table of results that was necessary to show the limiting coordinates of the rays reaching the receiver was produced by RWE92.FOR, a modification of the original program RWE9.FOR. Therefore the suit of programs required to produce this table, including VERN.FOR the program for the vernier reading equivalent of the x coordinate for the experiment, are:-

*	RWE92.FOR	main program.
	QUADRT.FOR	sub. for greatest quad. soln.
	QUADNG.FOR	sub. for smallest quad. soln.
	RAYJ1.FOR	sub. for direction evaluation.
	RAYJ2.FOR	sub. for direction evaluation.
	EFFY.FOR	sub. to output results.
	VOLUME.FOR	sub. for volume evaluation.
*	VERN.FOR	sub. for vernier reading.

These programs contain detailed program decomposition.

* new routines or versions resulting from this section are found in appendix B.

REFERENCES

2.1 J.S.P. (Jacksons Structured Programming). T1607 International Computers Limited (1978).

CHAPTER 3

SIMULATION OF HEAT TRANSFER AND TEMPERATURE DISTRIBUTION

3.1 INTRODUCTION

So far the heat loss from the collector has only been dealt with in an approximate manner. Its evaluation was based on the following assumptions.

1. No internal heat generation.

2. The temperature distribution was in a steady state.

3. The heat flow model was one dimensional.

4. The top and receiver boundaries were at prescribed temperatures.

This approximation was sufficient when considering so many different shapes since it provided results of the correct order of magnitude, however actual heat loss will depend on a number of factors, including geometry and internal heat generation. Therefore it would seem appropriate to study the heat loss from the chosen shape in much more detail.

This chapter describes the method of determining the heat loss of the collector under both steady and unsteady state conditions. The unsteady state being an extension of the steady state treatment.

To evaluate the temperature distribution within the collector the finite difference method of heat transfer has been chosen. This is because the elemental meshes required for this model are well suited to the collector, as shown in Fig.3.1. For instance the model chosen must be able to cope with both curved and straight boundary conditions, having both elements with energy

ELEMENTAL MESH

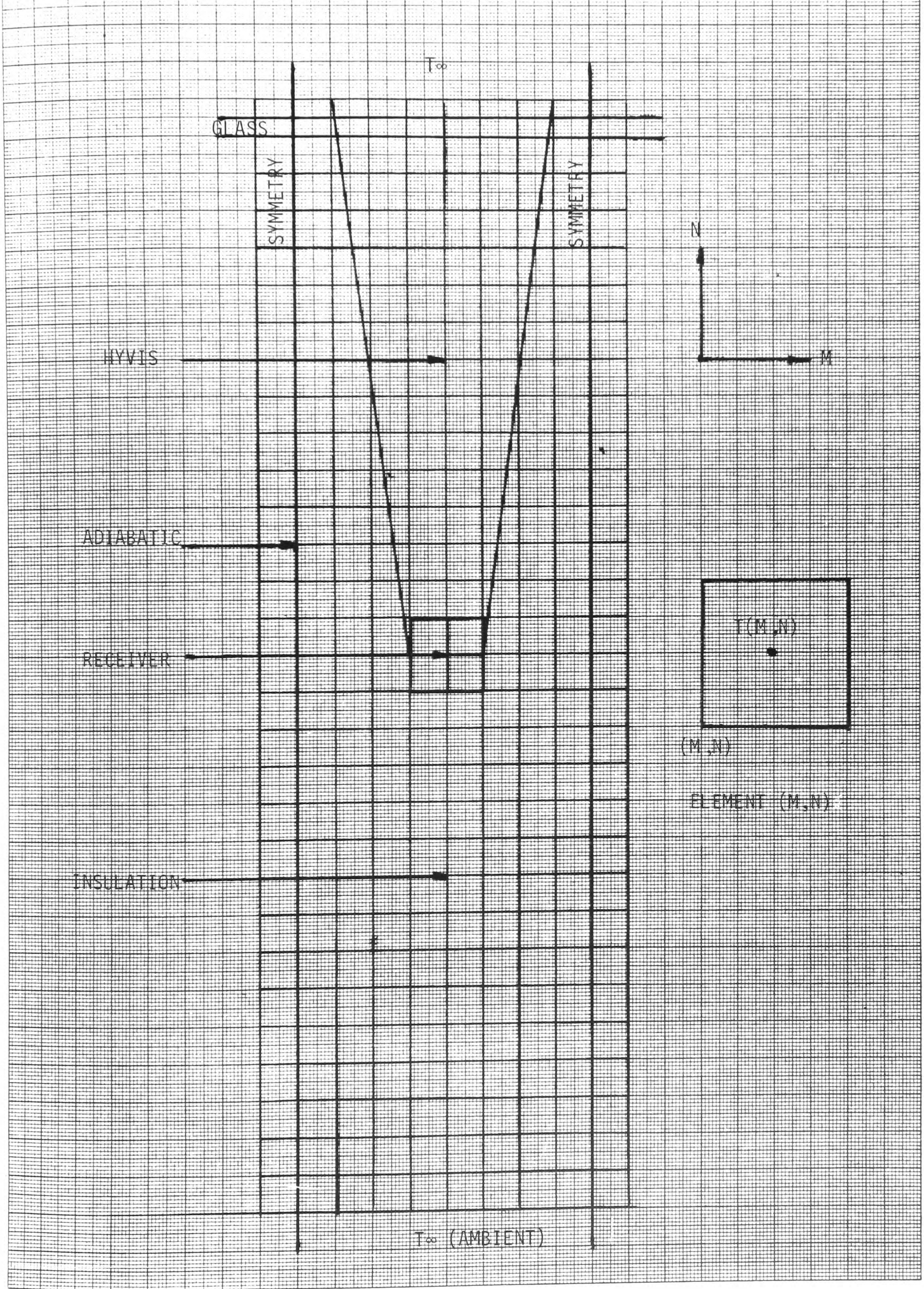


Fig 3.1

generation and those without, and capable of having variable thermal resistances and capacitances. Before the finite difference method can be used heat generation rates and thermal resistances for each mesh has to be evaluated. The rate of internal heat generation involved writing several programs to simulate the energy absorption rate in the Hyvis. Programs TAB.FOR, TABT.FOR and ENGEN.FOR are used to evaluate the elemental energy generation rate for each mesh. The thermal resistances are evaluated from the collector boundary conditions and its component thermal conductivities using program THMRES.FOR. Using this data the program FINDIF.FOR evaluates the temperature distribution at the elemental nodal points for steady state conditions.

To evaluate the temperature distribution under unsteady conditions it is necessary to evaluate the elemental thermal capacities of each mesh, this is achieved by program MASCAP.FOR which evaluates the energy required to raise each element through 1C.

Of the two methods for predicting the temperature distribution with time the explicit method has been adopted rather than the implicit method since the forward difference equations are much easier to solve and will save a considerable amount of computer time. For this the program HETCAP.FOR was written and from the resulting temperature distributions the graph of temperature versus time was produced.

The temperature distributions predicted by this program are shown at the end of section 3.5 & 3.6 and predict the collector has a high stagnation temperature indicating that it has a small heat loss and should perform well under any working conditions. By careful consideration it has been possible to predict the overall efficiency of the collector under steady state conditions which are presented in graphs of efficiency plotted against temperature rise per unit insolation.

It should be noted that very often in solar energy work energy is incorrectly used for power. However this is not a problem if it is always interpreted as being a rate of energy generation or as in other cases a rate of absorption.

All the programs described in this section are all listed in Appendix C.

3.2 THE STEADY STATE FINITE DIFFERENCE HEAT TRANSFER MODEL

This section is concerned with the heat loss from the receiver by conduction and although the collector is three dimensional we only need consider a two dimensional model. This is merely due to the collector's shape having a uniform cross section throughout its length. It can be assumed that the temperature distribution for any cross section is identical and therefore heat transfer along the axis of the collector is not possible.

The finite difference method is a commonly used analitical scheme of determining temperature distributions and heat flow in solids having complicated geometries, boundary conditions and temperature dependant properties. The first step in the analysis is the transformation of the differential equation of heat conduction into a set of algebraic equations for temperature at a number of nodal points over the region.

Consider the Fourier {ref.3.1} two dimensional steady state heat conduction equation with energy generation given in the form:-

$$\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} + \frac{g(x,y)}{K} = 0$$

Then by adopting the finite difference method described by Ozisik {ref.3.1} this equation simplifies to:-

$$[T_{m-1,n}+T_{m+1,n}+T_{m,n-1}+T_{m,n+1}-4T_{m,n}] + g_{m,n}L^2/K = 0$$

A more general expression which allows for the variation of thermal conductivity with position {ref.3.1} can be written in terms of thermal resistances. Considering node p contained within the volume element V_p and its four neighbouring nodes as shown in Fig.3.2 we have:-

$$\text{for } j=1 \text{ to } 4 \qquad \frac{[T_j - T_p]}{R_{jp}} + V_p g_p = 0$$

where the elemental side is L and

$R_{jp} = \left(\frac{L}{KA}\right)_{jp}$ is the thermal resistance between nodes j and p

V_p the volume of the element about node p

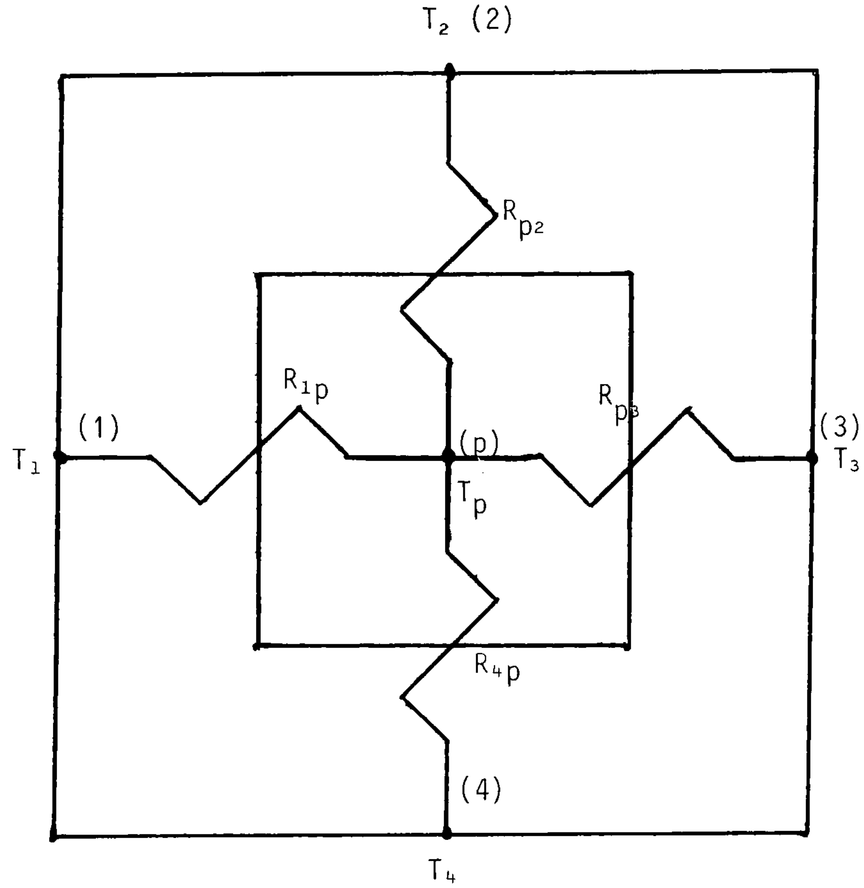
g_p the energy generation rate per unit volume at node p

The boundary conditions required for the collector are prescribed temperature for the top and bottom surfaces and adiabatic for the sides. The top and bottom of the collector are defined by the ambient temperature assumed to be 20C throughout the simulation. While the side boundaries lie symmetrically between the collector channels subsequently the temperature on either side is assumed equal with no heat flow across the boundary.

At a prescibed temperature boundary the actual temperature of the neighbouring node is substituted into the equation.

At an abiabatic boundary the temperature of the neighbouring node is given the same temperature as the elemental node.

In order to apply the above equation, a rectangular mesh of size L^2 is constructed over the collector cross section and associated insulation as shown in Fig.3.1. For each element the energy generation rate and thermal resistances between the nodes had to be determined.



NOMENCLATURE FOR ENERGY BALANCE AT NODE P

Fig 3.2

3.3 THE HEAT GENERATION SYSTEM

As light passes through the Hyvis energy is absorbed, this absorption is refered to as the heat generation within the Hyvis and its evaluation is obtained from the equation of solar energy transmittance in Hyvis, derived in chapter 4.3.1. The rate of absorption in each element of the finite difference mesh can be calculated by evaluating the absorption of each ray as it passes through the collector and is achieved by the routine TAB.FOR which is patched into the ray tracking simulation. This routine produces a data file ENERGY-TEMP.DAT containing the percentage of incidence energy absorbed in each element of the mesh for each angle of incidence considered. From this data file the conversion program ENGEN.FOR produces the file ENGEN.DAT which contains the fraction of incident energy per unit volume absorbed in each element per second.

These programs and their respective data files can be found in the appendices. Two systems are documented, namely those associated with TAB.FOR which have been developed with a mesh size of 1 cm and those associated with TABT.FOR that have a size of 0.5 cm. The derived temperature distributions from the finite difference equations for the two mesh sizes have been compared and observe a 2% variation. This was considered sufficiently accurate since there is a limit to the use of very small mesh sizes due to increased computational round of errors and the computer time required.

The amount of energy left in the ray when it reaches the receiver is considered to be absorbed into the mesh element at that point, and is treated in the same way as the other heat generation elements. For this case no energy gain by the transfer fluid has been considered and simulates the 0% efficiency or stagnation situation. To simulate the energy gained by the transfer fuid, various percentages 0,25,50,75 and 100 of the energy generation within the receiver elements have been removed. For these different energy gains the steady state temperature distributions and collector efficiencies have been calculated. Since the rate of energy generation for a fixed geometry is assumed to be a function of insolation, the energy gain by the transfer fluid is also a function of insolation. Two important facts can be gathered from this, namely that since temperature is a function of energy generation the resulting temperature distribution is only a function of insolation, and that under these conditions collector efficiency is unchange by insolation. This has been verified by repeating the simulation of the steady state case for different insolation values and angles of incidence.

3.3.1 THE EQUATIONS OF ABSORPTION AND REFLECTION

From the transmission of energy in Hyvis equation (section 4.3.1) where I is the percentage of transmission and RLOP is the length of path in cm. we have :-

$$I = -9.8 \log(RLOP) + 80.6$$

This assumes that when RLOP = 0.1, I = 90.4

The other 9.6% of the incoming energy can be accounted for as:-

4% reflection.

5.6% absorption in the first mm.

Without reflection for RLOP = 0.1 ; I would be 94.4%
giving the general equation:-

$$I = -9.8 \log(RLOP) + 84.6$$

If R is the fraction of energy lost by reflection calculated from Fresnel's relationship {ref.3.2} then it is possible to evaluate an apparent depth of Hyvis that would produce the equivalent absorption. If this new apparent path length is RLOP' then from the above equation we have:-

$$I - R*100 = -9.8 \log(RLOP') + 84.6$$

$$94.4-R*100 = -9.8 \log(RLOP') + 84.6$$

giving an apparent depth of Hyvis of:-

$$RLOP' = 10^{[(84.6+R*100-94.4)/9.8]}$$

For a 4% loss due to reflection the eqivalent path length through the Hyvis would be 0.256cm.

THE ENERGY ABSORBED BY THE SIDE SURFACE DUE TO REFLECTION:
The reflectance of the Aluminized Polyester film is 0.9 {ref.3.2} therefore the apparent path length of a ray in Hyvis to account for an equivalent amount of energy absorbed, where RLOP is the length of path before reflection and RLOP' is the apparent length after reflection is:-

$$I = -9.8 \log(RLOP) + 84.6$$

$$0.9I = -9.8 \log(RLOP') + 84.6$$

giving:-

$$RLOP' = 10^{[0.8633 + 0.9 \log(RLOP)]}$$

RLOP in cm.

This equation is used within TAB.FOR to account for the energy absorption due to reflection.

THE FRESNEL RELATIONSHIP FOR THE REFLECTION OF NON-POLARIZED RADIATION:
The reflectance of an interface between two refractive indicies where Q_1 and Q_2 are the angles of incidence and refraction has been derived by Fresnel {ref.3.2} as:-

$$p=I_r/I_o=0.5[\sin^2(Q_2-Q_1)/\sin^2(Q_2+Q_1)$$
$$+\tan^2(Q_2-Q_1)/\tan^2(Q_2+Q_1)]$$

and where Snell's law is:-

$$n_1/n_2 = \sin Q_1/\sin Q_2$$

and the transmittance of a single reflection is:-

$$T_r = 1 - p$$

Then as the limit of $Q_1\rightarrow$ $Q_2\rightarrow$ 0 the equation simplifies to:-

$$p = [(n_1-n_2)/(n_1+n_2)]^2$$

and when one medium is air ie. $n_1=1$ we have:-

$$p = [(n-1)/(n+1)]^2$$

These relationships are used in the modified ray tracking simulation program RWE11.FOR to work out the energy losses for different angles of incidence at the top surface.

3.3.2 ELEMENTAL ABSORPTION OF SOLAR ENERGY (TAB.FOR)

The transmittance of solar energy in Hyvis has been measured experimentally (section 4.3.1), however the finite difference method of heat transfer requires the amount of energy that is absorbed throughout the grid. The method adopted evaluates the absorption in each element of the mesh for every ray entering the collector. In the optimisation program the segment of each ray's path between each change of direction has already been defined, it therefore remains to truncate this segment for the mesh in order to obtain the absorption in each element for each segment. The resulting program therefore analyses each segment of ray evaluated by the optimisation program. The objective was therefore to write a program that simulates the attenuation of light as it passes through the collector. It should be able to perform the summation of the energy absorbed in each element and finally produce a table of the total energy absorbed in each element of the mesh for the entire incident beam. This can be modularized by the following steps:-

1. Define the segment under consideration and identify its direction.(Fig.3.3).
2. Calculate the length of the ray and the energy absorbed in each element of the mesh.
3. Include the energy absorbed at points of reflection in the elemental structure.

The procedures required to perform this algorithm must therefore be able to superimpose the segment of the ray's path onto the elemental array shown at Fig.3.3. It must then identify the type of trajectory that occurs in each element. This has been defined by the rays starting and finishing sides on each element. There are four cases to consider in each direction quadrant and are shown at Figures 3.4; 3.5; 3.6 and 3.7. After each element has been considered the new length of ray is evaluated before the absorption in the next element along the path can be considered. The details of these procedures have been described in the structure diagrams shown at Fig.3.8 and Fig.3.9.

3.3.3 PROGRAMS FOR THE HEAT GENERATION SYSTEM

The following suit of programs have been written or altered for the heat generation system with a mesh size of 1 cm.

*	RWE11.FOR	main program.
	QUADRT.FOR	sub. for greatest quad. soln.
	QUADNG.FOR	sub. for smallest quad. soln.
	RAYJ1.FOR	sub. for direction evaluation.
	RAYJ2.FOR	sub. for direction evaluation.
	EFFY.FOR	sub. to output results.
	VOLUME.FOR	sub. for volume evaluation.
*	TAB.FOR	sub. for elemental heat gen.
*	TABCNT.FOR	sub. for totalling heat gen.
*	TRAP2.FOR	sub. for receiver elements.

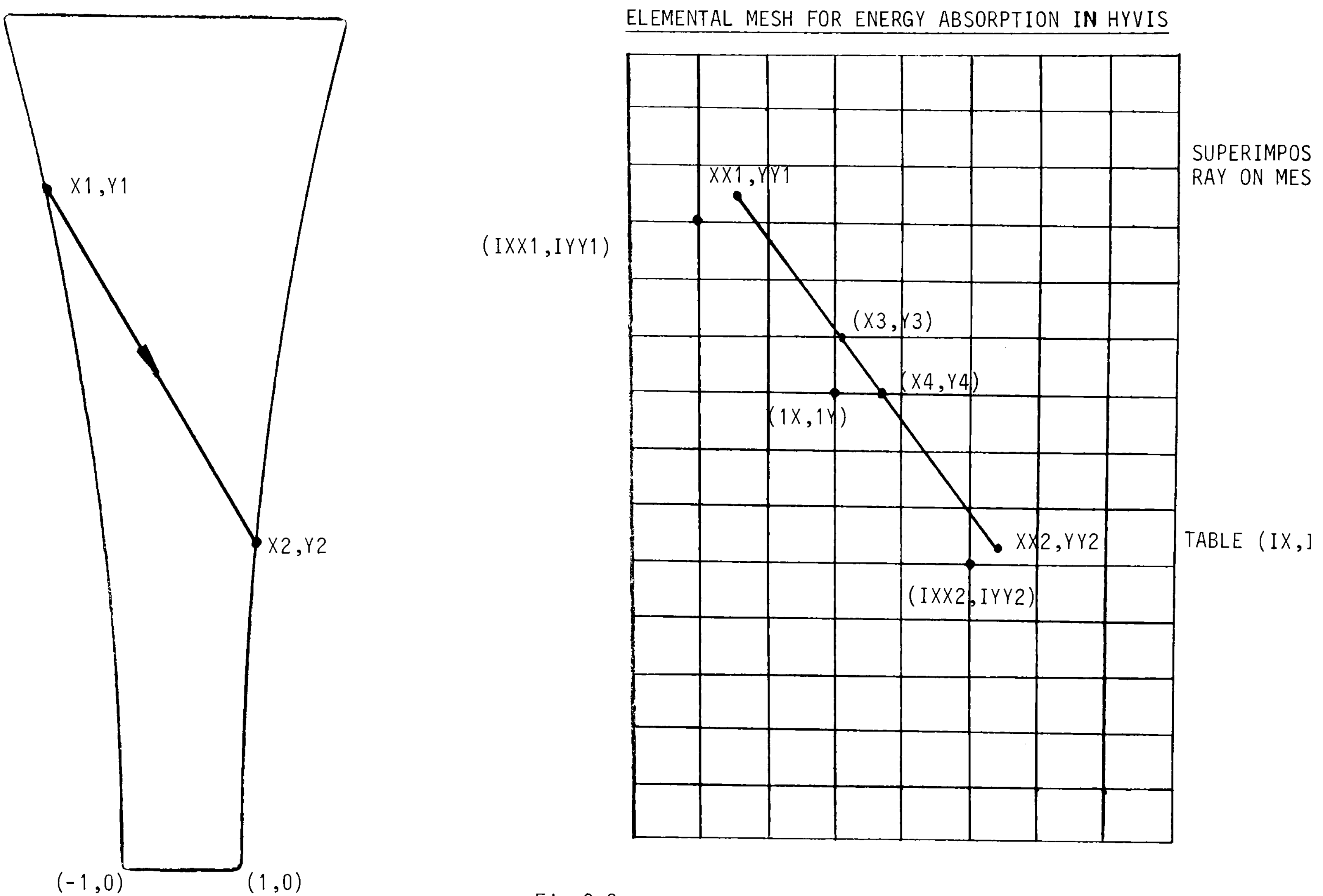
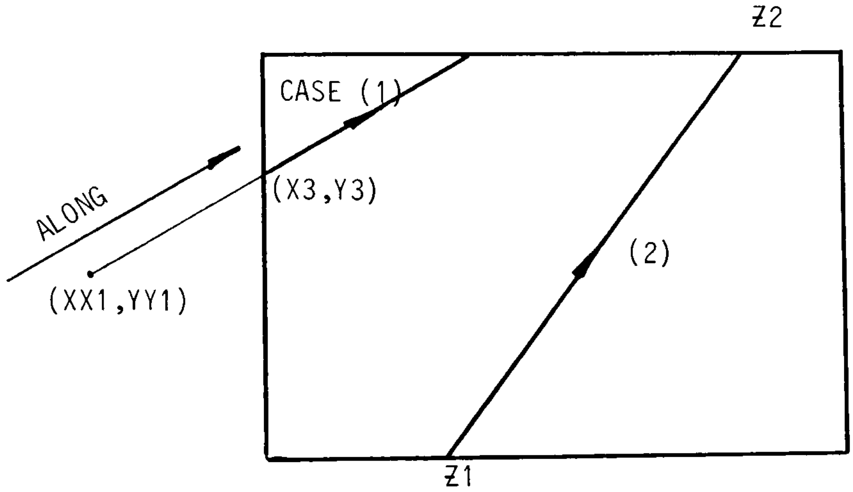

X1,Y1
X2,Y2
(-1,0)
(1,0)
ELEMENTAL MESH FOR ENERGY ABSORPTION IN HYVIS
SUPERIMPOS
RAY ON MES
XX1,YY1
(IXX1,IYY1)
(X3,Y3)
(X4,Y4)
(1X,1Y)
XX2,YY2
(IXX2,IYY2)
TABLE (IX,]

Fig 3.3

FOUR CASES TO CONSIDER FOR A RAY WITH DIRECTION IN THE FIRST QUADRANT



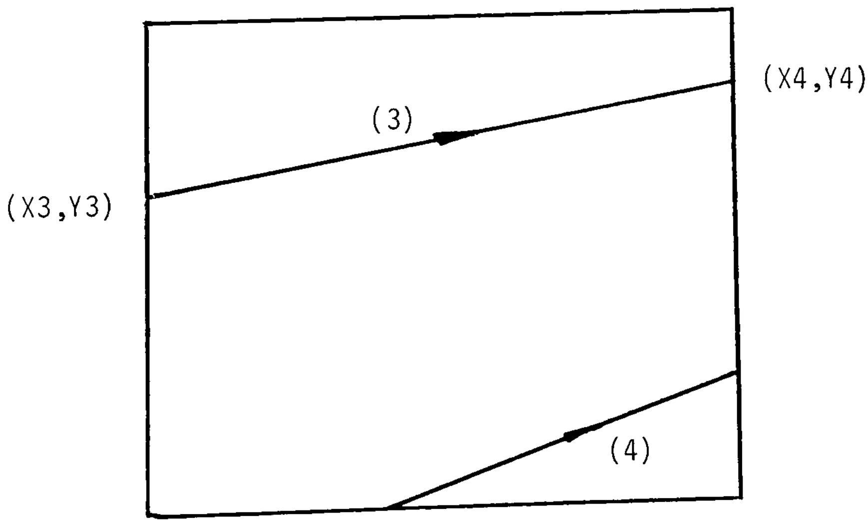


Fig 3.4

FOUR CASES TO CONSIDER FOR A RAY WITH DIRECTION IN THE SECOND QUADRANT

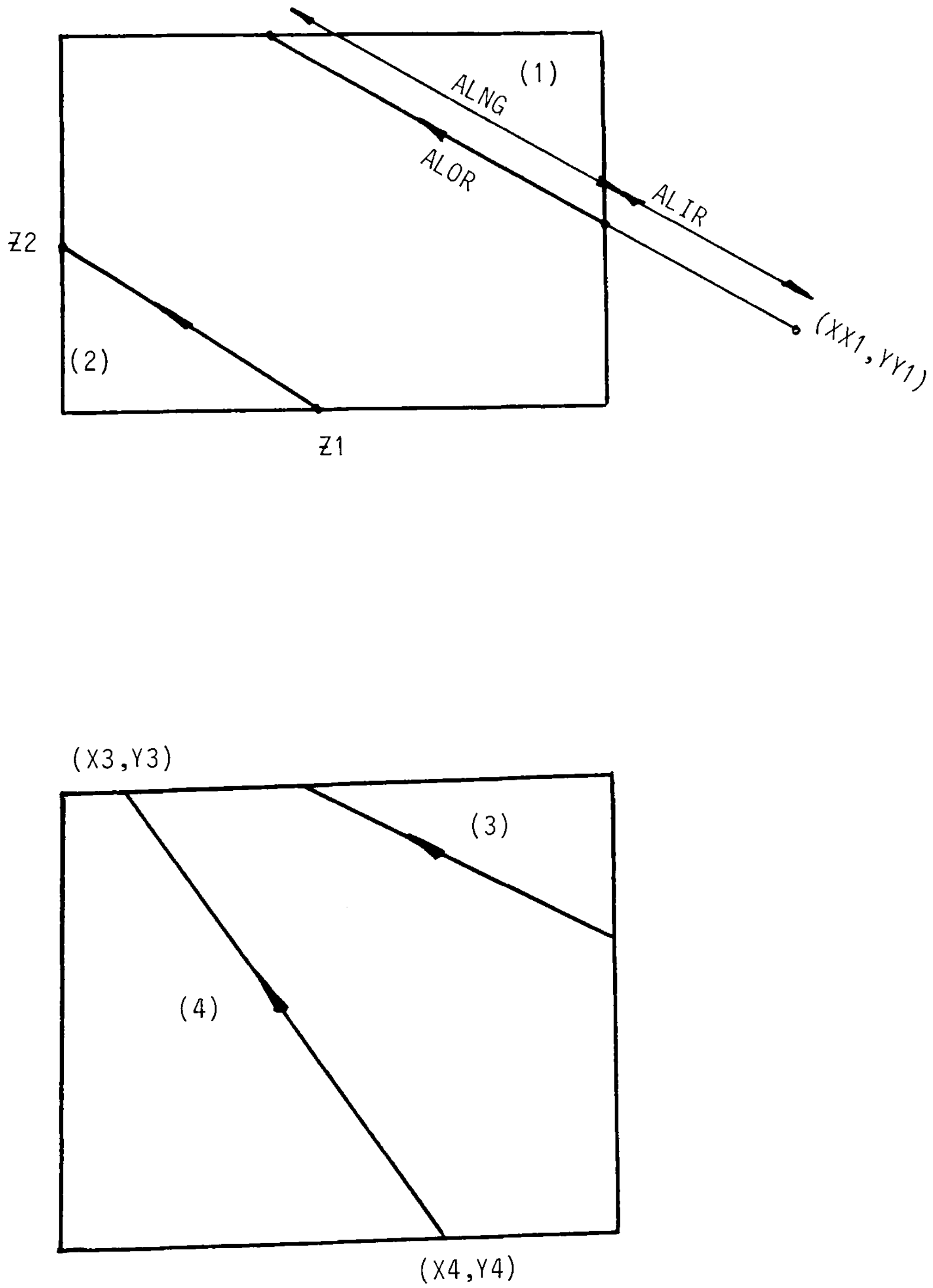


Fig. 3.5

FOUR CASES TO CONSIDER FOR A RAY WITH DIRECTION IN THE THIRD QUADRANT

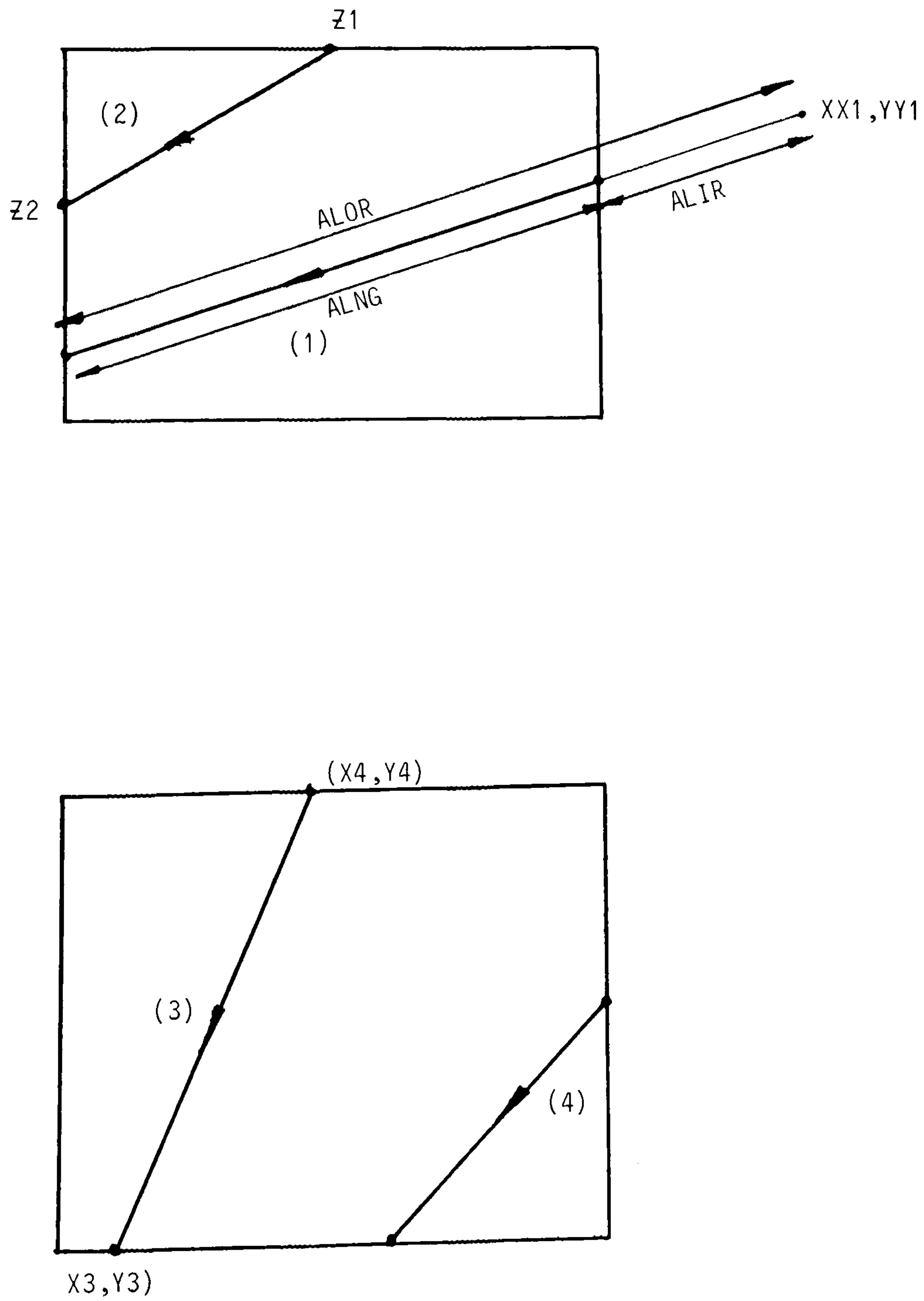


Fig 3.6

FOUR CASES TO CONSIDER FOR A RAY WITH DIRECTION IN THE FOURTH QUADRANT

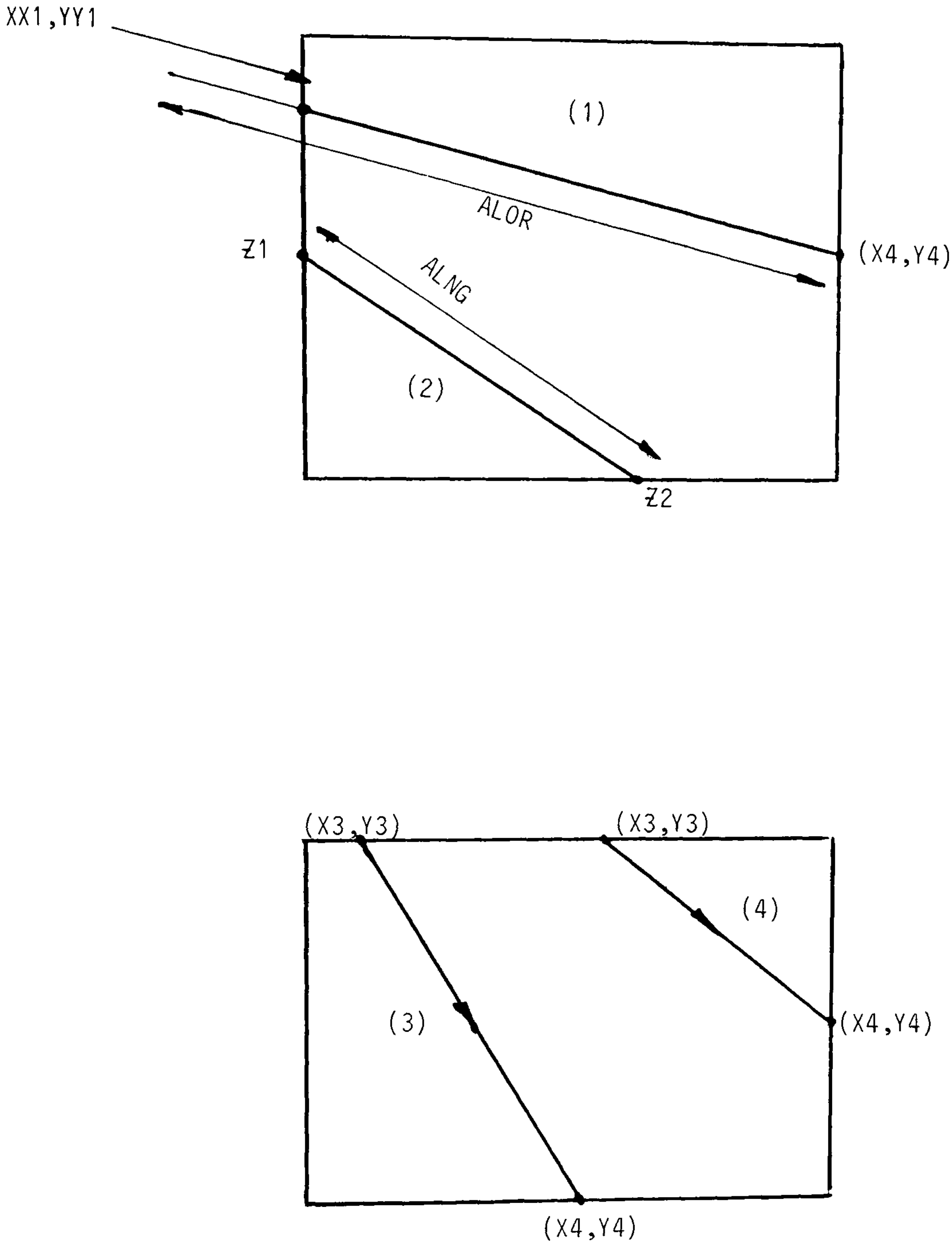


Fig 3.7

STRUCTURE DIAGRAM FOR HEAT GENERATION PROGRAM (TAB.FOR)

The summation of the energy absorbed by the Hyvis.

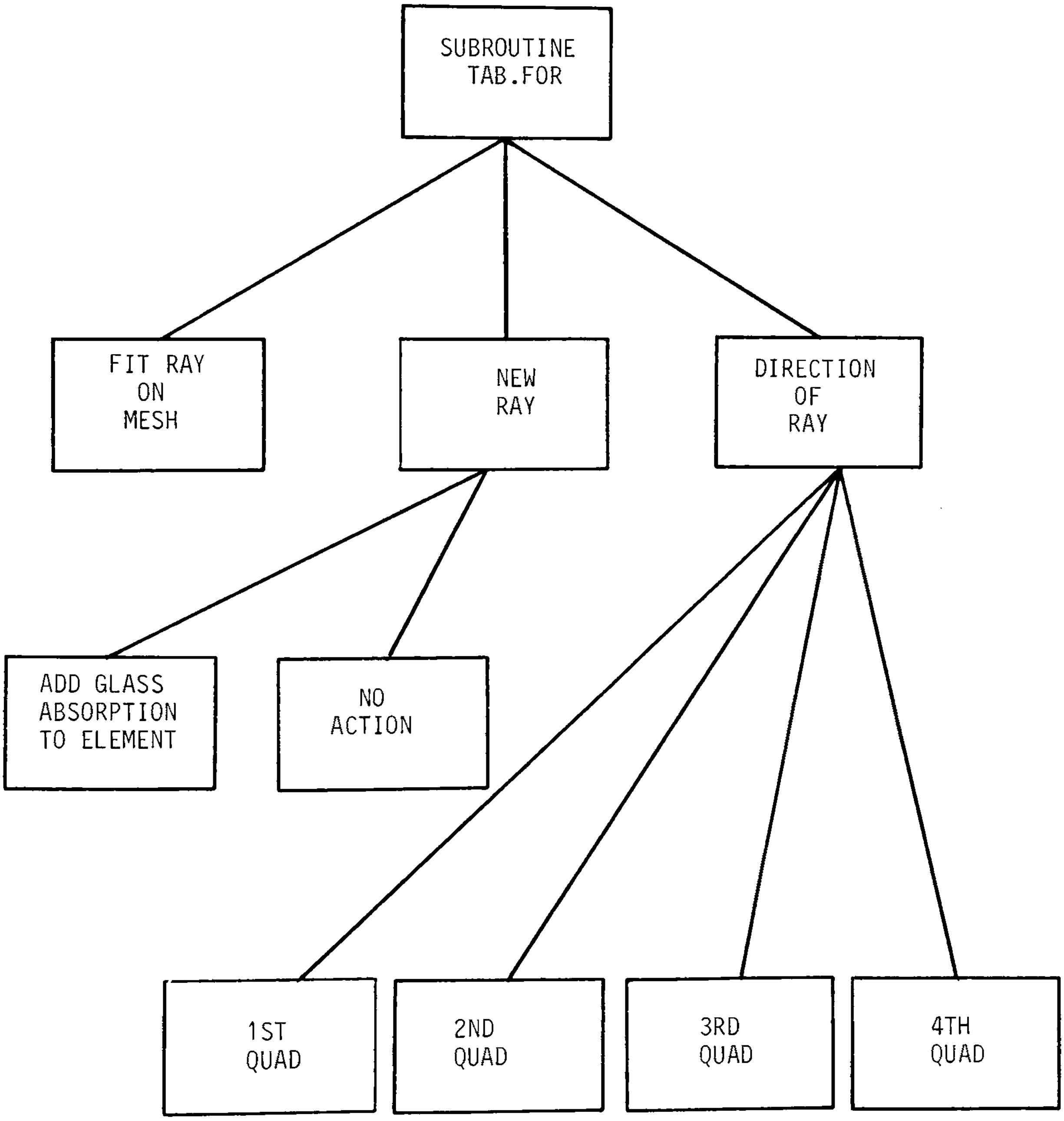


Fig. 3.8

THE STRUCTURE DIAGRAM FOR A RAY IN THE SECOND QUADRANT

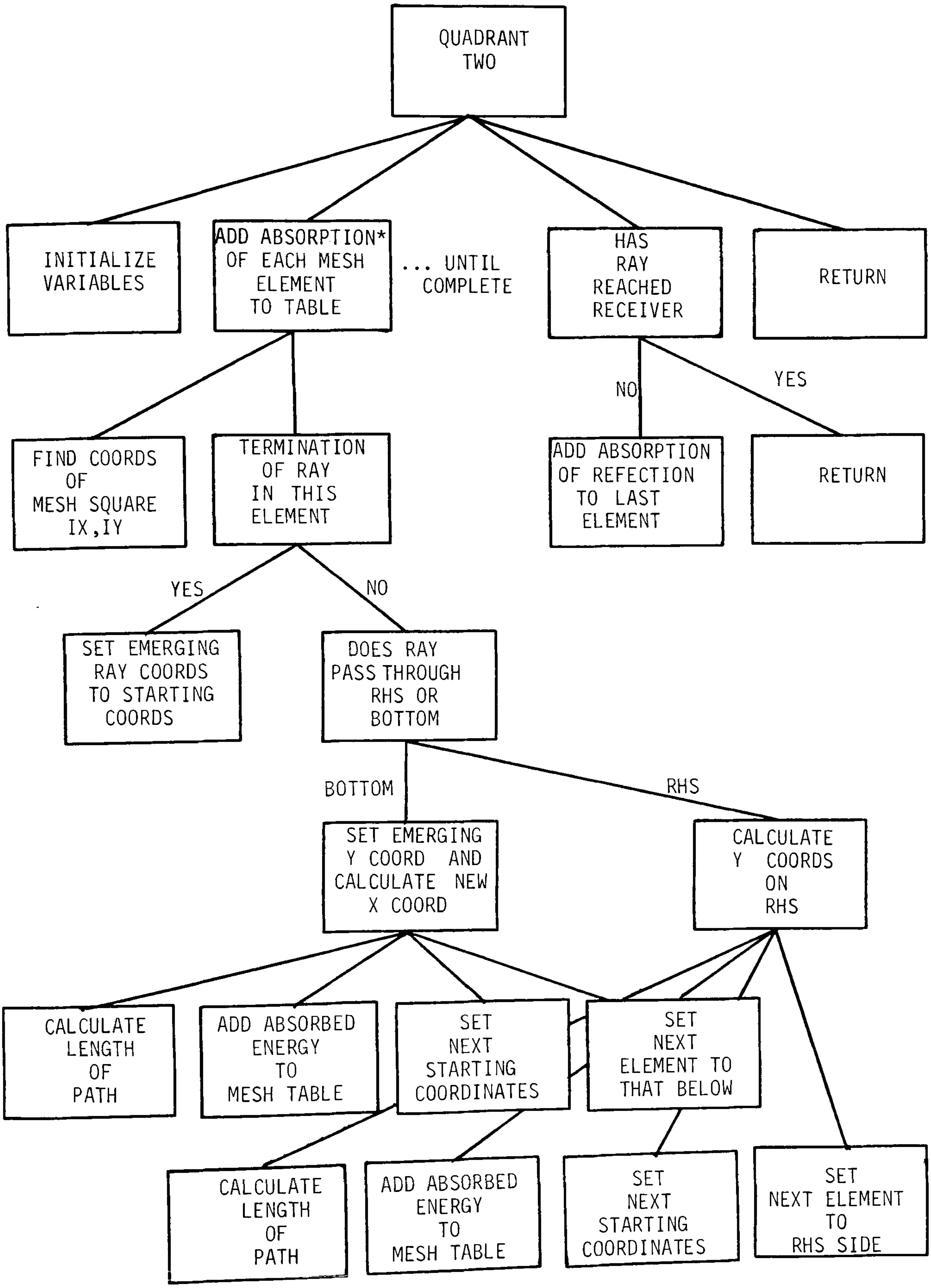


Fig 3.9

These programs contain detailed program decomposition.

* new routines or versions resulting from this section are listed in appendix C.

The resulting data from this simulation ENERGY_TEMP.DAT is not listed, but has been used as data by the program ENGEN.FOR to predict the energy generation per unit insolation in section 3.3.5.

It was considered instructive to repeat this routine for all possible angles of incidence as this would indicate the effect of diffuse radiation on the collector. Although the quantity of diffuse radiation is small its effect helps to cut down heat loss by heating the Hyvis near the top of the collector. It was found that 22.5% of diffuse radiation is absorbed by the receiver and 48% absorbed in the Hyvis. Giving a total of 70.73% of diffuse radiation performing some useful function.

3.3.4 PROGRAMS FOR THE HEAT GENERATION SYSTEM

The following suit of programs have been written or altered for the heat generation system with a mesh size of 0.5 cm.

*	RWE11T.FOR	main program.
	QUADRT.FOR	sub. for greatest quad. soln.
	QUADNG.FOR	sub. for smallest quad. soln.
	RAYJ1.FOR	sub. for direction evaluation.
	RAYJ2.FOR	sub. for direction evaluation.
	EFFY.FOR	sub. to output results.
	VOLUME.FOR	sub. for volume evaluation.
*	TABT.FOR	sub. for elemental heat gen.
*	TABCNTT.FOR	sub. for totalling heat gen.
*	TRAP2T.FOR	sub. for receiver elements.

These programs contain detailed program decomposition.

* new routines or versions resulting from this section and are listed in appendix C. The resulting data from this simulation ENERGY__TEMPT.DAT is not listed but has been compared with the results for the larger grid size with good conformity.

3.3.5 HEAT GENERATION CONVERSION PROGRAM ENGEN.FOR

The absorption of energy throughout the grid is now available as a percentage of insolation, this however is not in the correct format for the finite difference equation and therefore needs to be modified. These values although remaining a function of insolation must be quoted as an energy generation per unit volume. It must also be remembered that the energy reaching the receiver is also treated in the same manner and will depend on the percentage of energy reaching the receiver that is allowed to escape to the transfer fluid. The energy generation for the receiver is therefore given separately for each of the five different heat loss situations.

The objective of the resulting program is to convert the elemental percentage energies of data file ENERGY_TEMP.DAT into unit energy generation per unit volume. Included should be the facility to alter the energy loss from the receiver elements in 25% steps by recording alternative values for the receiver elements.

This has been modularized into the following steps:-

1. Reading the data file ENERGY_TEMP.DAT.
2. Convert and write into heat generation array.
3. Write to data file.
4. Process the heat generation values for the receiver elements and repeat for 0,25,50,75 and 100% heat loss.
5. Write alternative elemental receiver energy loss values to data file.

In order to perform the conversion the following factors must be derived. If the insolation beam is E wm^{-2} and the collector is s metres wide then Q the power incident on the collector per unit length is:-

$$Q = Es \quad W$$

If P is the percentage of energy absorbed in each element and the volume of each element is L^2 m^3 then g the energy generation rate per unit volume in each element is:-

$$g = P\ E\ s\ /\ 100\ L^2 \quad Wm^{-3}$$

If both L and s are given in centimetres the equation becomes:-

$$g = P\ E\ s\ /\ L^2 \quad Wm^{-3}$$

The insolation levels are to be included at a latter stage so the new data file ENGEN.DAT will contain unit energy generation rate per unit volume per unit insolation giving:-

$$g' = g/E = P\ s\ /\ L^2 \quad m^{-1}$$

The procedures and actions required to perform this conversion are described by the structure diagram of Fig.3.10.

3.4 THE THERMAL RESISTANCE SYSTEM

Before the finite difference model can be implimented it is necessary to evaluate the thermal resistances between the nodes of the elemental mesh. Whereas thermal conductivity is a measure of the heat flow rate within a material thermal resistance is a measure of resistance to heat flow and is defined as :-

$$R = L/kA \quad CW^{-1}$$

Where k is the thermal conductivity, L the length and A the cross sectional area.

As in the case of the electrical analogy, thermal resistances in series may be added to give the total resistance while in parallel the method of reciprical addition is used.

The thermal resistances required can be divided into two sets

STRUCTURE DIAGRAM FOR PROGRAM (ENGEN.FOR)

This program produces the energy generation mesh.

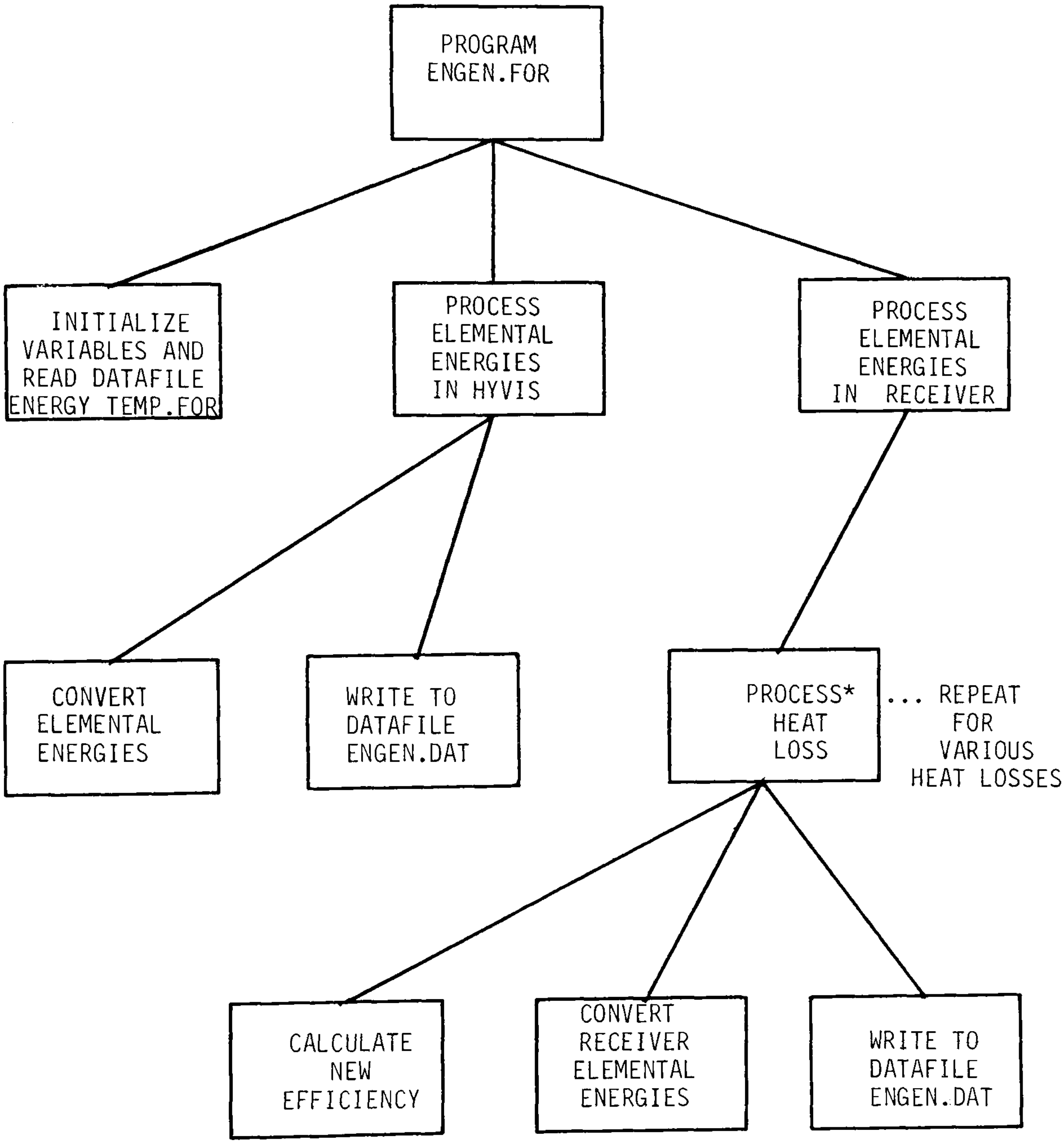


Fig 3.10

those that are horizontal and those that are vertical. Therfore associated with each node (m,n) are two thermal resistances R(m,n,1) horizontal and R(m,n,2) vertical as shown in Fig.3.11. Although both are independant of each other they both share the same symmetry about the y axis which can be refered to as a reflection at m=0. Therefore it can be expressed mathematically by the equations:-

$$R(m,n,1) = R(-m-2,n,1)$$

$$R(m,n,2) = R(-m-1,n,2)$$

The shift is required because the resistance R(m,n,1) represents the resistance between nodes (m,n) and (m+1,n) as shown in Fig.3.11. Using this symmetry the resistances at the positive nodes can be mapped onto their symmetrical counterparts while those below the receiver all have the value for insulation. The elemental values for the receiver can then be superimposed onto the existing grid.

It is therefore necessary to write a program that is capable of creating a data file containing all the horizontal and vertical thermal resistances required by either of the finite difference meshes, for the boundaries of the solar collector.

Many of the elements in the mesh contain a composite of different materials, which are treated as a combination of either series or parallel thermal resistances. The elemental composite thermal resistance cases that are encountered within the collector are as follows:-

1. Composite in series.
2. Node outside boundary (vertical).
3. Composite in series and parallel combined (vertical).
4. Unchanging material (vertical).
5. Composite in parallel (vertical).
6. Composite in series (horizontal).
7. Unchanging material (horizontal).

THE THERMAL RESISTANCE MESH

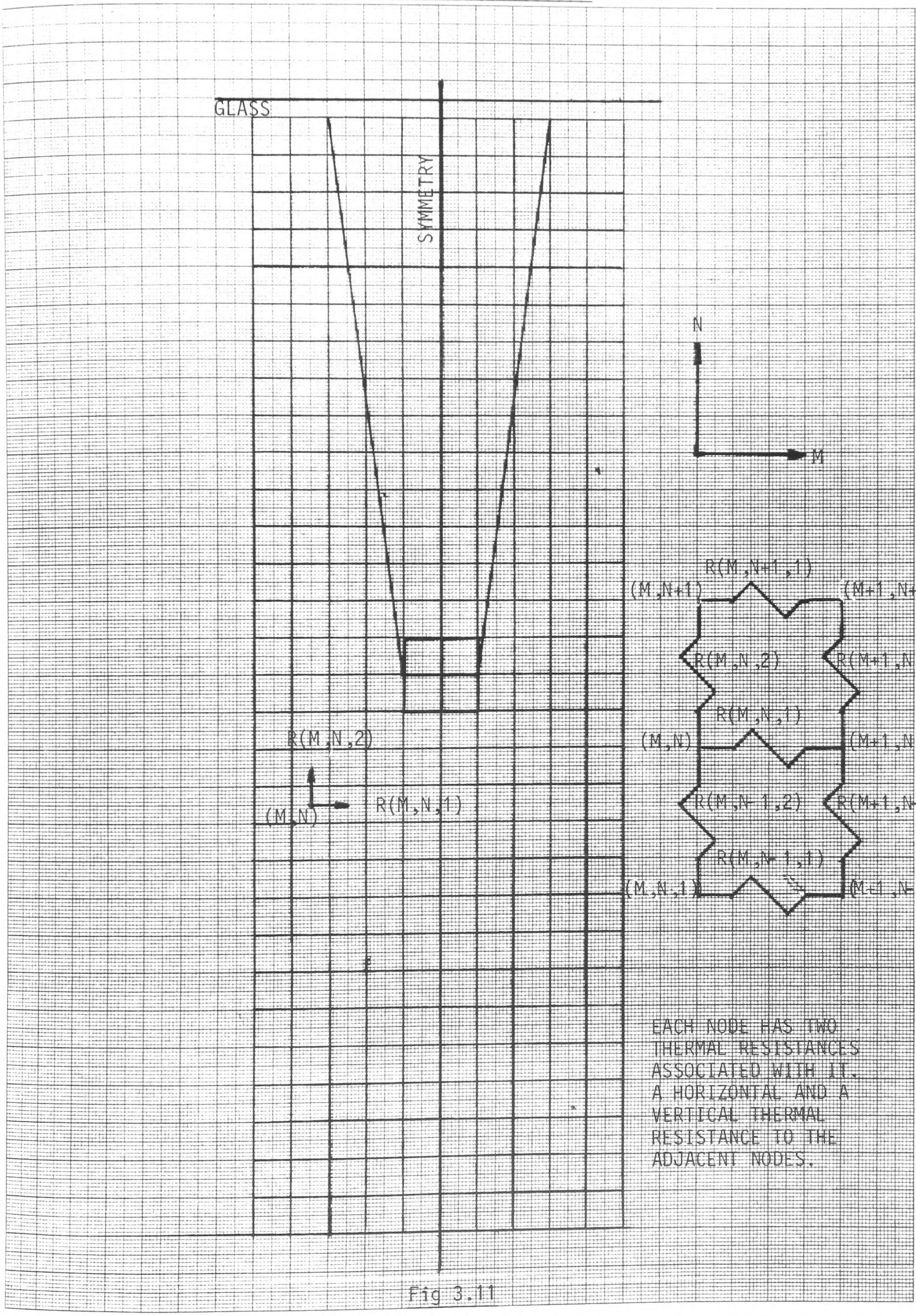


Fig 3.11

The proceedures required to perform this program are set out in the structure diagram of Fig.3.12. While below is a detailed evaluation for each of the composite cases listed above.

THE CASES OF COMPOSITE THERMAL RESISTANCES:

Where thermal resistance is defined as:-

$$R = L/kA$$

and since for any element of either mesh MOD(L) = MOD(A) the equation can be simplifies to:-

$$R = 1/k$$

CASE 1

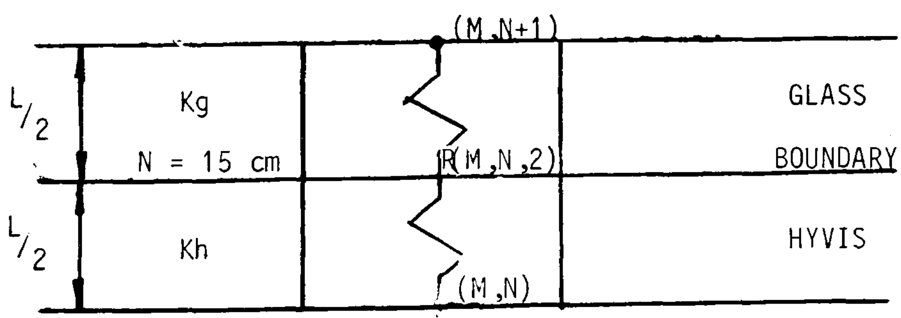
The series thermal resistance between Hyvis and glass or insulation and glass.

1hg. For Hyvis and glass.

$$R(m,n,2) = (L/2)/(Lkh) + (L/2)/(Lkg) = (kh+kg)/2khkg$$

1ig. For insulation and glass.

$$R(m,n,2) = (L/2)/(Lki) + (L/2)/(Lkg) = (ki+kg)/2kikg$$



STRUCTURE DIAGRAM FOR THERMAL RESISTANCES PROGRAM (THMRES.FOR)

This program creates the datafile THERMRES.DAT which contains the required thermal resistances.

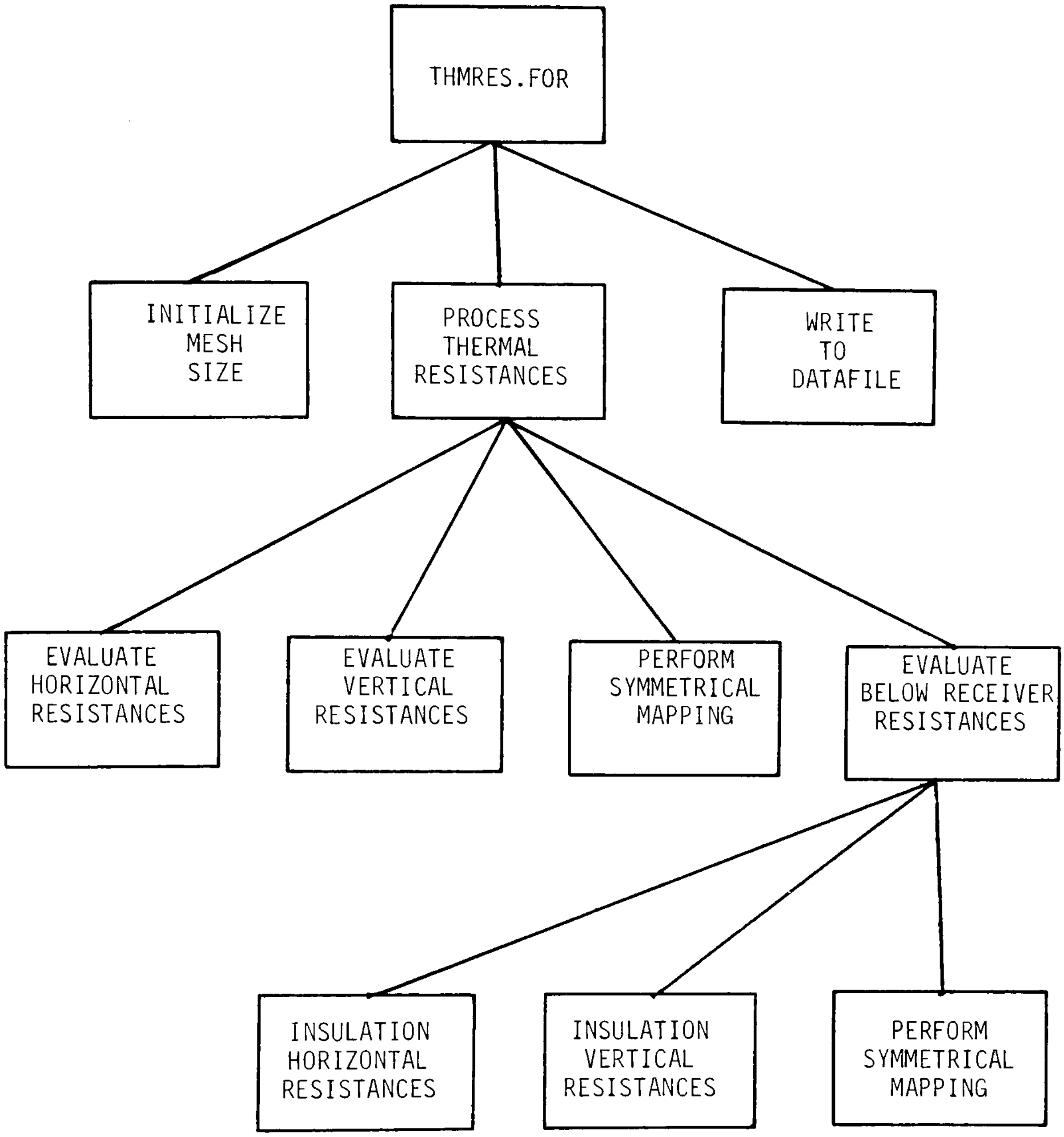


Fig 3.12

CASE 2

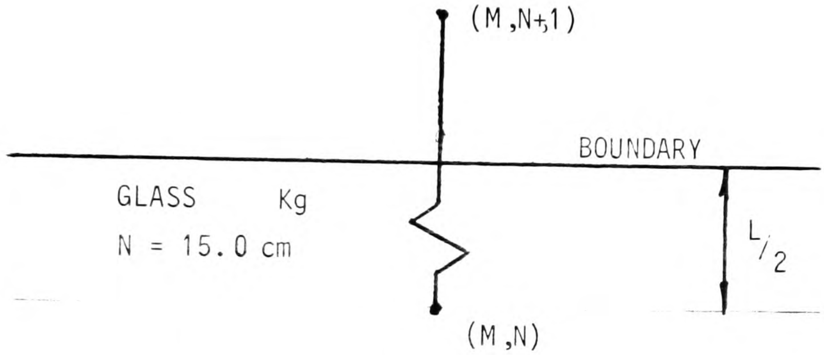
Node outside boundary between glass and air or insulation and air for the vertical case.

2g. For glass and air.

R(m,n,2) = (L/2)/Lkg = 1/2kg

2i. For insulation and air.

R(m,n,2) = (L/2)/Lki = 1/2ki



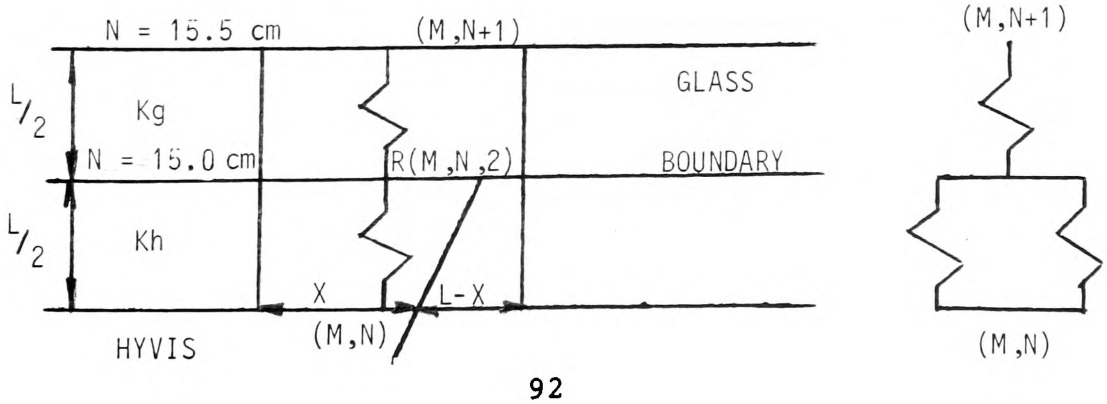
CASE 3

Composite in both series and parallel for the vertical resistance at the junction between the Hyvis, insulation and the glass top.

R(m,n,2) = (l/2)/lkg + (l/2)/(xkh+(l-x)ki

= 1/2kg + 1/2(xkh+(l-x)ki)

note x is the distance from the grid wall not the node.



CASE 4

Unchanging material between two vertical nodes.

4h. For Hyvis.

$R(m,n,2) = L/Lkh = 1/kh$

4i. For insulation.

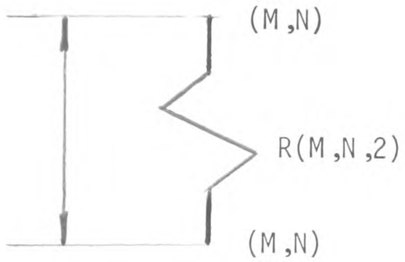
$R(m,n,2) = L/Lki = 1/ki$

4g. For glass.

$R(m,n,2) = L/Lkg = 1/kg$

4r. For receiver (copper).

$R(m,n,2) = L/Lkr = 1/kr$



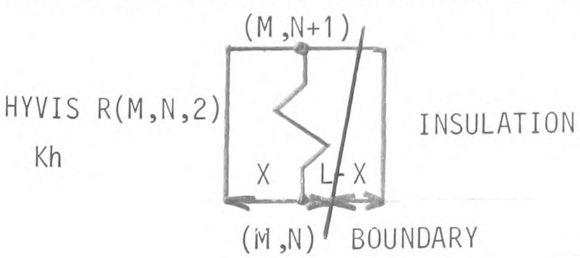
CASE 5

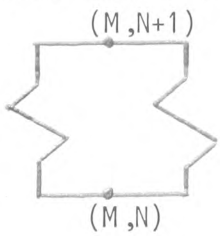
The parallel thermal resistance between Hyvis and glass for two vertical nodes.

$1/R(m,n,2) = xkh/L + (L-x)ki/L$

$R(m,n,2) = L/(xkh +(L-x)ki)$

Note x is not the distance from the node but from the grid wall.





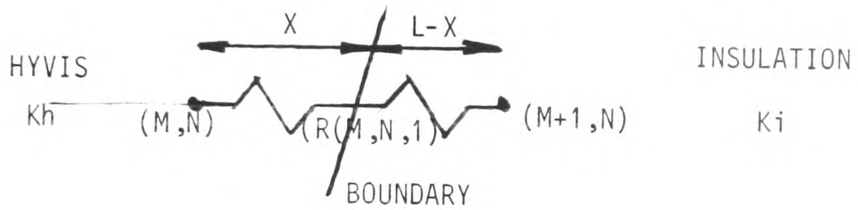
CASE 6

The series thermal resistance between Hyvis and insulation for two horizontal nodes.

R(m,n,1) = x/Lkh + (L-x)/Lki

= (xki+(L-x)kh)/Lkhki

Note x is the distance from the node.



CASE 7

unchanging material for two horizontal nodes.

7h. For Hyvis.

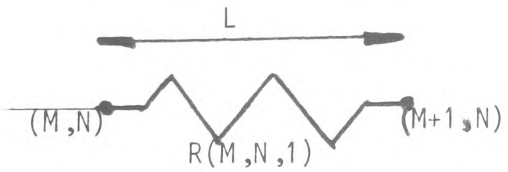
R(m,n,1) = L/Lkh = 1/kh

7g. For Glass.

R(m,n,1) = L/Lkg = 1/kg

7i. For insulation.

R(m,n,1) = L/Lki = 1/ki



3.5 THE STEADY STATE COLLECTOR TEMPERATURE DISTRIBUTION

Once the elemental heat generation and thermal resistances have been evaluated it is possible to evaluate the temperature distribution throughout the collector for various collector efficiencies under steady state conditions. Using the equation defined at section 3.2 for each element, results in a set of n algebraic equations where n is the number of temperatures nodes. The solution of these can be found using matrices. There are therefore two parts to the solution of the temperature distribution by the finite difference method, creating the energy balance linear equations for each element of the network and solving the resulting matrices. The construction of the equations has been carried out by the program FINDIF.FOR while their solution has been found using the subroutine SOLMAT.FOR which makes use of NAG Library routine F04ATF to solve the matrix equation and then writes the resulting temperature distribution to the data file MATTEMP.DAT.

The set of temperature distributions for normal radiation with an insolation of 900 Wm^{-2} are shown in TABLE 3.1-3.5. From them it can be seen that the stagnation temperature for these conditions is approximately 410C.

The objective is therefore to write the program FINDIF.FOR which will for various efficiencies and insolations produce an array of the finite difference equations that can be filed for further evaluation and processing. Then construct the routine SOLMAT.FOR that will solve the resulting matrix equation and produce the required temperature distribution. The program FINDIF.FOR can be simplified by considering each of the following steps:-

1. Define the mesh size and boundaries.
2. Read the data file of thermal resistances.
3. Repeat for the various insolation values to be used.
4. Repeat for different incidence values.
5. Read the data file of elemental heat generation.

DATA FILE: MATTEMP.DAT THE STEADY STATE TEMPERATURE DISTRIBUTION

The angle of the incident radiation is 0 degrees with insolation of 900 Watts per metre squared.
The efficiency of the collector is 64.50% and the ambient temperature is 20.00degrees centigrade.

DT/E = 0.046

20.03	20.06	20.19	20.19	20.20	20.21	20.22	20.22	20.22	20.22	20.22	20.21	20.19	20.19	20.06	20.03
21.14	21.01	20.50	21.42	21.70	21.80	21.84	21.86	21.86	21.84	21.80	21.70	21.43	20.51	21.01	21.15
23.45	23.42	23.45	23.93	24.20	24.34	24.42	24.46	24.46	24.43	24.35	24.21	23.95	23.47	23.44	23.47
25.77	25.79	25.83	26.43	26.61	26.75	26.83	26.87	26.87	26.84	26.76	26.64	26.46	25.87	25.82	25.81
28.09	28.13	28.20	28.74	28.92	29.04	29.12	29.17	29.17	29.14	29.06	28.95	28.79	28.25	28.18	28.13
30.36	30.44	30.63	30.94	31.12	31.25	31.33	31.37	31.37	31.34	31.28	31.17	31.00	30.69	30.49	30.42
32.56	32.64	32.81	33.06	33.26	33.39	33.46	33.50	33.51	33.48	33.42	33.31	33.13	32.87	32.70	32.62
34.68	34.75	34.88	35.08	35.35	35.47	35.54	35.58	35.58	35.56	35.51	35.41	35.16	34.95	34.81	34.74
36.74	36.79	36.88	36.94	37.41	37.50	37.56	37.60	37.60	37.59	37.54	37.47	37.02	36.95	36.86	36.80
38.74	38.79	38.90	39.08	39.35	39.46	39.53	39.57	39.58	39.56	39.50	39.42	39.15	38.97	38.86	38.80
40.68	40.74	40.87	41.06	41.26	41.38	41.46	41.50	41.51	41.48	41.42	41.33	41.13	40.93	40.81	40.75
42.57	42.63	42.75	42.94	43.15	43.27	43.34	43.39	43.40	43.37	43.31	43.22	43.01	42.82	42.70	42.63
44.40	44.46	44.58	44.76	45.00	45.13	45.20	45.25	45.25	45.23	45.17	45.07	44.83	44.64	44.52	44.46
46.16	46.22	46.35	46.53	46.75	46.97	47.03	47.06	47.07	47.05	47.01	46.83	46.59	46.41	46.28	46.22
47.86	47.93	48.06	48.25	48.46	48.79	48.82	48.84	48.84	48.85	48.83	48.53	48.31	48.12	47.98	47.91
49.49	49.57	49.72	49.94	50.21	50.60	50.57	50.56	50.57	50.59	50.64	50.26	49.99	49.77	49.62	49.54
51.05	51.14	51.31	51.58	51.97	52.35	52.25	52.21	52.22	52.27	52.37	52.00	51.62	51.35	51.18	51.09
52.51	52.61	52.81	53.11	53.53	53.93	53.82	53.76	53.77	53.83	53.96	53.56	53.15	52.85	52.65	52.55
53.88	53.99	54.20	54.53	54.96	55.41	55.28	55.21	55.22	55.29	55.44	54.98	54.56	54.24	54.02	53.92
55.14	55.26	55.49	55.83	56.28	56.78	56.62	56.55	56.55	56.64	56.80	56.30	55.86	55.52	55.29	55.17
56.29	56.41	56.66	57.03	57.51	58.06	57.85	57.75	57.76	57.86	58.09	57.54	57.06	56.69	56.44	56.32
57.31	57.45	57.72	58.13	58.67	59.36	58.94	58.82	58.83	58.95	59.39	58.70	58.15	57.74	57.47	57.33
58.19	58.34	58.64	59.08	59.68	60.44	59.86	59.74	59.74	59.87	60.46	59.70	59.11	58.66	58.36	58.22
58.93	59.09	59.41	59.89	60.53	61.33	60.61	60.48	60.48	60.62	61.36	60.55	59.91	59.43	59.11	58.95
59.51	59.67	60.01	60.53	61.22	62.11	61.19	61.05	61.05	61.20	62.13	61.24	60.55	60.03	59.69	59.52
59.91	60.09	60.45	60.99	61.73	62.69	61.59	61.43	61.44	61.59	62.70	61.74	61.00	60.46	60.11	59.93
60.15	60.33	60.69	61.25	62.01	62.98	61.79	61.63	61.63	61.79	62.99	62.02	61.26	60.70	60.34	60.16
60.20	60.38	60.74	61.30	62.08	63.14	61.79	61.64	61.64	61.79	63.15	62.09	61.31	60.75	60.39	60.21
60.08	60.25	60.60	61.14	61.88	62.87	61.56	61.47	61.47	61.56	62.88	61.89	61.14	60.61	60.26	60.09
59.78	59.94	60.27	60.76	61.42	62.27	61.32	61.32	61.32	61.32	62.27	61.43	60.77	60.28	59.95	59.79
59.31	59.47	59.77	60.23	60.78	61.32	61.32	61.32	61.32	61.32	61.32	60.79	60.23	59.78	59.47	59.32
58.70	58.84	59.14	59.58	60.17	60.91	61.32	61.32	61.32	61.32	60.91	60.17	59.58	59.14	58.85	58.70
57.94	58.07	58.35	58.78	59.42	60.40	61.32	61.32	61.32	61.32	60.40	59.42	58.78	58.35	58.08	57.94
57.04	57.16	57.40	57.78	58.31	59.04	59.97	60.19	60.19	59.97	59.05	58.32	57.78	57.40	57.16	57.04
56.02	56.12	56.32	56.62	57.02	57.49	57.97	58.18	58.18	57.97	57.50	57.02	56.62	56.32	56.12	56.03
54.91	54.98	55.14	55.36	55.64	55.95	56.22	56.37	56.37	56.22	55.95	55.64	55.36	55.14	54.99	54.91
53.71	53.77	53.89	54.05	54.24	54.44	54.61	54.70	54.70	54.61	54.44	54.24	54.05	53.89	53.77	53.72
52.46	52.50	52.59	52.70	52.83	52.97	53.07	53.13	53.13	53.07	52.97	52.83	52.70	52.59	52.51	52.46
51.17	51.20	51.26	51.34	51.43	51.51	51.58	51.62	51.62	51.58	51.51	51.43	51.34	51.26	51.20	51.17
49.84	49.86	49.90	49.96	50.02	50.08	50.13	50.15	50.15	50.13	50.08	50.02	49.96	49.90	49.86	49.84
48.49	48.51	48.54	48.58	48.62	48.66	48.69	48.70	48.70	48.69	48.66	48.62	48.58	48.54	48.51	48.50
47.13	47.14	47.16	47.19	47.22	47.24	47.26	47.27	47.27	47.26	47.24	47.22	47.19	47.16	47.14	47.13
45.76	45.77	45.78	45.80	45.82	45.84	45.85	45.86	45.86	45.85	45.84	45.82	45.80	45.78	45.77	45.76
44.38	44.39	44.39	44.41	44.42	44.43	44.44	44.45	44.45	44.44	44.43	44.42	44.41	44.39	44.39	44.38
43.00	43.00	43.01	43.01	43.02	43.03	43.04	43.04	43.04	43.04	43.03	43.02	43.01	43.01	43.00	43.00
41.61	41.61	41.61	41.62	41.63	41.63	41.64	41.64	41.64	41.64	41.63	41.63	41.62	41.61	41.61	41.61
40.22	40.22	40.22	40.23	40.23	40.23	40.24	40.24	40.24	40.24	40.23	40.23	40.23	40.22	40.22	40.22
38.83	38.83	38.83	38.83	38.83	38.84	38.84	38.84	38.84	38.84	38.84	38.83	38.83	38.83	38.83	38.83
37.43	37.43	37.44	37.44	37.44	37.44	37.44	37.44	37.44	37.44	37.44	37.44	37.44	37.44	37.43	37.43
36.04	36.04	36.04	36.04	36.04	36.04	36.05	36.05	36.05	36.05	36.04	36.04	36.04	36.04	36.04	36.04
34.65	34.65	34.65	34.65	34.65	34.65	34.65	34.65	34.65	34.65	34.65	34.65	34.65	34.65	34.65	34.65
33.25	33.25	33.25	33.25	33.25	33.25	33.25	33.25	33.25	33.25	33.25	33.25	33.25	33.25	33.25	33.25
31.86	31.86	31.86	31.86	31.86	31.86	31.86	31.86	31.86	31.86	31.86	31.86	31.86	31.86	31.86	31.86
30.46	30.46	30.46	30.46	30.46	30.46	30.46	30.46	30.46	30.46	30.46	30.46	30.46	30.46	30.46	30.46
29.07	29.07	29.07	29.07	29.07	29.07	29.07	29.07	29.07	29.07	29.07	29.07	29.07	29.07	29.07	29.07
27.67	27.67	27.67	27.67	27.67	27.67	27.67	27.67	27.67	27.67	27.67	27.67	27.67	27.67	27.67	27.67
26.28	26.28	26.28	26.28	26.28	26.28	26.28	26.28	26.28	26.28	26.28	26.28	26.28	26.28	26.28	26.28
24.88	24.88	24.88	24.88	24.88	24.88	24.88	24.88	24.88	24.88	24.88	24.88	24.88	24.88	24.88	24.88
23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49	23.49
22.09	22.09	22.09	22.09	22.09	22.09	22.09	22.09	22.09	22.09	22.09	22.09	22.09	22.09	22.09	22.09
20.70	20.70	20.70	20.70	20.70	20.70	20.70	20.70	20.70	20.70	20.70	20.70	20.70	20.70	20.70	20.70

TABLE 3.1

DATA FILE: MATTEMP.DAT THE STEADY STATE TEMPERATURE DISTRIBUTION

The angle of the incident radiation is 0 degrees with insolation of 900 Watts per metre squared.
The efficiency of the collector is 48.38% and the ambient temperature is 20.00degrees centigrade.

DT/E = 0.143

20.05	20.10	20.28	20.28	20.31	20.33	20.34	20.34	20.35	20.34	20.33	20.31	20.28	20.29	20.10	20.05
22.00	21.72	20.77	22.30	22.78	22.97	23.05	23.09	23.09	23.06	22.97	22.79	22.31	20.77	21.73	22.01
26.10	25.93	25.69	26.61	27.14	27.44	27.61	27.68	27.68	27.61	27.45	27.16	26.63	25.71	25.95	26.12
30.38	30.24	29.91	31.09	31.52	31.83	32.03	32.13	32.13	32.04	31.85	31.54	31.12	29.95	30.27	30.41
34.80	34.72	34.54	35.39	35.85	36.18	36.40	36.51	36.52	36.42	36.21	35.88	35.43	34.59	34.76	34.84
39.30	39.30	39.36	39.65	40.16	40.52	40.75	40.87	40.87	40.77	40.55	40.21	39.71	39.42	39.35	39.35
43.81	43.81	43.84	43.93	44.50	44.88	45.11	45.23	45.24	45.13	44.91	44.55	44.00	43.90	43.87	43.87
48.32	48.29	48.23	48.13	48.91	49.27	49.49	49.61	49.62	49.52	49.30	48.97	48.21	48.30	48.35	48.38
52.85	52.80	52.66	52.25	53.37	53.68	53.90	54.02	54.03	53.93	53.72	53.43	52.33	52.73	52.87	52.92
57.44	57.41	57.36	57.33	57.70	58.08	58.34	58.46	58.47	58.36	58.13	57.77	57.40	57.43	57.48	57.51
62.06	62.05	62.03	62.05	62.14	62.55	62.81	62.95	62.96	62.84	62.59	62.21	62.11	62.10	62.11	62.12
66.69	66.68	66.66	66.65	66.66	67.07	67.35	67.50	67.50	67.38	67.12	66.72	66.72	66.73	66.74	66.76
71.34	71.32	71.29	71.24	71.20	71.68	71.96	72.10	72.11	71.98	71.73	71.27	71.31	71.35	71.38	71.40
76.00	75.98	75.93	75.84	75.66	76.40	76.64	76.76	76.77	76.66	76.44	75.73	75.90	75.99	76.04	76.05
80.67	80.66	80.62	80.51	80.23	81.18	81.37	81.47	81.48	81.39	81.22	80.30	80.57	80.68	80.72	80.73
85.36	85.37	85.38	85.37	85.32	85.97	86.14	86.22	86.23	86.16	86.01	85.37	85.42	85.43	85.42	85.41
90.05	90.08	90.15	90.27	90.48	90.81	90.93	90.99	91.00	90.94	90.84	90.52	90.31	90.19	90.12	90.09
94.70	94.76	94.88	95.07	95.34	95.62	95.72	95.77	95.77	95.73	95.64	95.37	95.10	94.92	94.79	94.73
99.28	99.37	99.54	99.79	100.11	100.43	100.50	100.55	100.55	100.52	100.45	100.13	99.82	99.57	99.40	99.32
103.79	103.90	104.12	104.43	104.82	105.22	105.28	105.32	105.32	105.30	105.24	104.84	104.46	104.15	103.93	103.82
108.18	108.32	108.60	109.00	109.49	110.01	110.06	110.08	110.08	110.07	110.03	109.51	109.03	108.63	108.35	108.21
112.43	112.61	112.97	113.48	114.12	114.87	114.81	114.80	114.81	114.82	114.90	114.15	113.51	112.99	112.64	112.45
116.49	116.72	117.18	117.83	118.65	119.60	119.50	119.48	119.49	119.51	119.63	118.68	117.85	117.20	116.75	116.52
120.32	120.62	121.19	122.01	123.05	124.24	124.12	124.10	124.10	124.13	124.26	123.07	122.03	121.21	120.64	120.35
123.87	124.23	124.94	125.98	127.30	128.85	128.68	128.66	128.66	128.69	128.87	127.32	126.00	124.96	124.25	123.89
127.05	127.49	128.37	129.66	131.34	133.34	133.18	133.16	133.16	133.18	133.35	131.36	129.68	128.38	127.51	127.06
129.79	130.32	131.37	132.96	135.06	137.59	137.61	137.62	137.62	137.61	137.60	135.07	132.98	131.39	130.33	129.80
132.00	132.61	133.85	135.75	138.35	141.68	142.01	142.05	142.05	142.01	141.69	138.36	135.76	133.87	132.62	132.01
133.60	134.28	135.68	137.84	140.90	145.06	146.41	146.49	146.49	146.41	145.07	140.90	137.85	135.69	134.29	133.61
134.51	135.24	136.73	139.05	142.34	146.88	148.73	148.73	148.73	148.73	146.88	142.34	139.05	136.73	135.25	134.52
134.70	135.43	136.94	139.29	142.52	146.60	148.73	148.73	148.73	148.73	146.60	142.52	139.29	136.95	135.44	134.70
134.14	134.86	136.33	138.63	141.86	146.14	148.73	148.73	148.73	148.73	146.14	141.87	138.63	136.34	134.86	134.15
132.87	133.53	134.89	137.04	140.16	144.79	148.73	148.73	148.73	148.73	144.79	140.16	137.04	134.90	133.54	132.87
130.93	131.51	132.67	134.47	136.96	140.19	143.90	144.82	144.82	143.90	140.19	136.96	134.47	132.68	131.51	130.93
128.42	128.89	129.82	131.21	133.02	135.10	137.06	137.93	137.93	137.06	135.10	133.02	131.21	129.82	128.89	128.42
125.44	125.80	126.51	127.53	128.79	130.14	131.30	131.90	131.90	131.30	130.14	128.79	127.53	126.51	125.80	125.44
122.10	122.37	122.89	123.62	124.48	125.36	126.09	126.49	126.49	126.09	125.36	124.48	123.62	122.89	122.37	122.10
118.49	118.69	119.06	119.57	120.16	120.74	121.21	121.47	121.47	121.21	120.74	120.16	119.57	119.06	118.69	118.49
114.69	114.83	115.09	115.44	115.84	116.23	116.54	116.71	116.71	116.54	116.23	115.85	115.44	115.09	114.83	114.69
110.75	110.84	111.03	111.27	111.54	111.80	112.01	112.12	112.12	112.01	111.80	111.54	111.27	111.03	110.85	110.75
106.71	106.78	106.90	107.07	107.25	107.43	107.56	107.64	107.64	107.56	107.43	107.25	107.07	106.90	106.78	106.71
102.60	102.65	102.74	102.85	102.98	103.09	103.18	103.23	103.23	103.18	103.09	102.98	102.85	102.74	102.65	102.60
98.45	98.48	98.54	98.62	98.70	98.78	98.85	98.88	98.88	98.85	98.78	98.70	98.62	98.54	98.48	98.45
94.27	94.29	94.33	94.38	94.44	94.49	94.53	94.56	94.56	94.53	94.49	94.44	94.38	94.33	94.29	94.27
90.06	90.08	90.10	90.14	90.18	90.22	90.24	90.26	90.26	90.24	90.22	90.18	90.14	90.10	90.08	90.06
85.84	85.85	85.87	85.89	85.92	85.95	85.96	85.97	85.97	85.96	85.95	85.92	85.89	85.87	85.85	85.84
81.61	81.62	81.63	81.65	81.66	81.68	81.69	81.70	81.70	81.69	81.68	81.66	81.65	81.63	81.62	81.61
77.37	77.38	77.39	77.40	77.41	77.42	77.43	77.43	77.43	77.43	77.42	77.41	77.40	77.39	77.38	77.37
73.13	73.13	73.14	73.15	73.16	73.16	73.17	73.17	73.17	73.17	73.16	73.16	73.15	73.14	73.13	73.13
68.88	68.89	68.89	68.90	68.90	68.91	68.91	68.91	68.91	68.91	68.91	68.90	68.90	68.89	68.89	68.88
64.64	64.64	64.64	64.64	64.65	64.65	64.66	64.66	64.66	64.66	64.65	64.65	64.65	64.64	64.64	64.64
60.39	60.39	60.39	60.39	60.40	60.40	60.40	60.40	60.40	60.40	60.40	60.40	60.39	60.39	60.39	60.39
56.14	56.14	56.14	56.14	56.14	56.15	56.15	56.15	56.15	56.15	56.15	56.14	56.14	56.14	56.14	56.14
51.89	51.89	51.89	51.89	51.89	51.89	51.89	51.89	51.89	51.89	51.89	51.89	51.89	51.89	51.89	51.89
47.64	47.64	47.64	47.64	47.64	47.64	47.64	47.64	47.64	47.64	47.64	47.64	47.64	47.64	47.64	47.64
43.39	43.39	43.39	43.39	43.39	43.39	43.39	43.39	43.39	43.39	43.39	43.39	43.39	43.39	43.39	43.39
39.13	39.13	39.13	39.13	39.13	39.13	39.14	39.14	39.14	39.14	39.13	39.13	39.13	39.13	39.13	39.13
34.88	34.88	34.88	34.88	34.88	34.88	34.88	34.88	34.88	34.88	34.88	34.88	34.88	34.88	34.88	34.88
30.63	30.63	30.63	30.63	30.63	30.63	30.63	30.63	30.63	30.63	30.63	30.63	30.63	30.63	30.63	30.63
26.38	26.38	26.38	26.38	26.38	26.38	26.38	26.38	26.38	26.38	26.38	26.38	26.38	26.38	26.38	26.38
22.13	22.13	22.13	22.13	22.13	22.13	22.13	22.13	22.13	22.13	22.13	22.13	22.13	22.13	22.13	22.13

TABLE 3.2

DATA FILE: MATTEMP.DAT THE STEADY STATE TEMPERATURE DISTRIBUTION

The angle of the incident radiation is 0 degrees with insolation of 900 Watts per metre squared.
The efficiency of the collector is 32.25% and the ambient temperature is 20.00degrees centigrade.

DT/E = 0.240

20.07	20.13	20.38	20.37	20.42	20.45	20.46	20.47	20.47	20.46	20.45	20.42	20.38	20.38	20.13	20.07
22.86	22.43	21.04	23.18	23.86	24.14	24.27	24.32	24.32	24.27	24.14	23.87	23.18	21.04	22.44	22.87
28.76	28.44	27.93	29.29	30.08	30.54	30.79	30.91	30.91	30.80	30.55	30.10	29.31	27.95	28.47	28.78
34.99	34.68	33.99	35.74	36.42	36.92	37.23	37.39	37.39	37.24	36.94	36.45	35.78	34.04	34.72	35.02
41.51	41.31	40.88	42.03	42.78	43.33	43.68	43.86	43.86	43.70	43.35	42.82	42.08	40.93	41.35	41.55
48.24	48.15	48.09	48.36	49.20	49.80	50.18	50.37	50.38	50.20	49.83	49.25	48.42	48.15	48.21	48.29
55.06	54.98	54.86	54.81	55.74	56.37	56.76	56.96	56.97	56.78	56.40	55.79	54.88	54.93	55.04	55.12
61.95	61.83	61.58	61.18	62.47	63.06	63.45	63.65	63.65	63.47	63.10	62.53	61.26	61.65	61.90	62.02
68.97	68.82	68.44	67.56	69.33	69.86	70.24	70.44	70.45	70.27	69.90	69.39	67.64	68.51	68.89	69.04
76.15	76.03	75.81	75.58	76.05	76.71	77.14	77.36	77.36	77.17	76.75	76.12	75.65	75.88	76.10	76.21
83.44	83.35	83.19	83.04	83.02	83.71	84.17	84.40	84.41	84.20	83.76	83.08	83.10	83.26	83.41	83.50
90.81	90.73	90.57	90.37	90.16	90.88	91.36	91.60	91.61	91.39	90.93	90.23	90.43	90.64	90.79	90.88
98.28	98.18	98.00	97.73	97.40	98.24	98.72	98.95	98.96	98.74	98.29	97.47	97.79	98.06	98.25	98.34
105.83	105.73	105.51	105.15	104.56	105.84	106.25	106.46	106.47	106.27	105.88	104.64	105.21	105.58	105.79	105.89
113.49	113.39	113.18	112.78	112.00	113.56	113.92	114.11	114.12	113.94	113.60	112.07	112.84	113.24	113.45	113.54
121.24	121.17	121.04	120.80	120.43	121.34	121.70	121.88	121.89	121.72	121.38	120.48	120.85	121.09	121.22	121.28
129.05	129.03	128.99	128.95	128.99	129.28	129.60	129.77	129.78	129.62	129.30	129.03	128.99	129.03	129.07	129.09
136.88	136.90	136.95	137.03	137.16	137.30	137.61	137.77	137.78	137.63	137.33	137.19	137.06	136.98	136.94	136.92
144.69	144.75	144.87	145.05	145.26	145.44	145.73	145.88	145.89	145.75	145.46	145.28	145.08	144.90	144.78	144.72
152.43	152.54	152.74	153.03	153.36	153.66	153.95	154.09	154.10	153.96	153.68	153.38	153.06	152.77	152.57	152.46
160.07	160.23	160.54	160.97	161.46	161.95	162.27	162.40	162.40	162.28	161.98	161.49	160.99	160.57	160.26	160.10
167.54	167.77	168.22	168.83	169.58	170.38	170.68	170.78	170.79	170.70	170.41	169.60	168.86	168.24	167.80	167.57
174.79	175.11	175.72	176.58	177.62	178.77	179.14	179.23	179.23	179.15	178.79	177.65	176.60	175.74	175.13	174.81
181.72	182.14	182.97	184.14	185.57	187.15	187.63	187.72	187.73	187.64	187.17	185.60	184.16	182.99	182.17	181.74
188.23	188.78	189.87	191.43	193.39	195.59	196.17	196.27	196.28	196.18	195.61	193.41	191.45	189.89	188.80	188.25
194.18	194.89	196.29	198.34	200.95	203.99	204.76	204.89	204.89	204.77	204.00	200.97	198.35	196.30	194.91	194.20
199.43	200.30	202.06	204.68	208.11	212.19	213.43	213.60	213.60	213.43	212.20	208.12	204.69	202.07	200.32	199.44
203.80	204.84	206.96	210.20	214.61	220.22	222.22	222.45	222.45	222.23	220.23	214.62	210.21	206.98	204.86	203.81
207.12	208.31	210.75	214.55	219.91	227.25	231.26	231.51	231.51	231.26	227.26	219.92	214.56	210.76	208.32	207.13
209.24	210.53	213.18	217.33	223.25	231.49	236.13	236.13	236.13	236.13	231.49	223.25	217.34	213.19	210.54	209.25
210.08	211.40	214.11	218.35	224.26	231.88	236.14	236.14	236.14	236.14	231.88	224.26	218.35	214.12	211.41	210.08
209.58	210.88	213.53	217.68	223.56	231.38	236.14	236.14	236.14	236.14	231.38	223.56	217.69	213.53	210.88	209.59
207.80	208.99	211.44	215.30	220.91	229.18	236.14	236.14	236.14	236.14	229.18	220.91	215.30	211.44	209.00	207.80
204.82	205.85	207.94	211.16	215.60	221.33	227.84	229.45	229.45	227.84	221.33	215.61	211.16	207.95	205.86	204.83
200.82	201.65	203.32	205.80	209.01	212.70	216.15	217.68	217.68	216.15	212.70	209.01	205.80	203.32	201.66	200.82
195.98	196.62	197.88	199.70	201.94	204.32	206.37	207.44	207.44	206.37	204.33	201.94	199.71	197.89	196.62	195.98
190.49	190.97	191.89	193.19	194.73	196.28	197.57	198.27	198.27	197.57	196.28	194.73	193.19	191.90	190.97	190.49
184.52	184.87	185.53	186.44	187.49	188.52	189.34	189.80	189.80	189.34	188.52	187.49	186.44	185.53	184.87	184.53
178.21	178.46	178.92	179.55	180.26	180.95	181.49	181.79	181.79	181.49	180.95	180.26	179.55	178.92	178.46	178.21
171.65	171.83	172.15	172.58	173.07	173.52	173.89	174.08	174.08	173.89	173.53	173.07	172.58	172.15	171.83	171.65
164.92	165.04	165.27	165.56	165.89	166.20	166.44	166.57	166.57	166.44	166.20	165.89	165.56	165.27	165.04	164.92
158.07	158.16	158.31	158.51	158.73	158.94	159.10	159.19	159.19	159.10	158.94	158.73	158.51	158.31	158.16	158.07
151.14	151.20	151.30	151.44	151.59	151.73	151.84	151.90	151.90	151.84	151.73	151.59	151.44	151.30	151.20	151.14
144.15	144.19	144.26	144.36	144.46	144.56	144.63	144.67	144.67	144.63	144.56	144.46	144.36	144.26	144.19	144.15
137.13	137.15	137.20	137.27	137.34	137.40	137.45	137.48	137.48	137.45	137.40	137.34	137.27	137.20	137.15	137.13
130.07	130.09	130.12	130.17	130.21	130.26	130.29	130.31	130.31	130.29	130.26	130.22	130.17	130.12	130.09	130.07
123.00	123.01	123.04	123.07	123.10	123.13	123.15	123.16	123.16	123.15	123.13	123.10	123.07	123.04	123.01	123.00
115.92	115.93	115.94	115.96	115.98	116.00	116.02	116.03	116.03	116.02	116.00	115.98	115.96	115.94	115.93	115.92
108.83	108.83	108.84	108.86	108.87	108.89	108.90	108.90	108.90	108.90	108.89	108.87	108.86	108.84	108.83	108.83
101.73	101.73	101.74	101.75	101.76	101.77	101.78	101.78	101.78	101.78	101.77	101.76	101.75	101.74	101.73	101.73
94.63	94.63	94.64	94.64	94.65	94.66	94.66	94.66	94.66	94.66	94.66	94.65	94.64	94.64	94.63	94.63
87.53	87.53	87.53	87.53	87.54	87.54	87.55	87.55	87.55	87.55	87.54	87.54	87.53	87.53	87.53	87.53
80.42	80.42	80.42	80.43	80.43	80.43	80.43	80.44	80.44	80.43	80.43	80.43	80.43	80.42	80.42	80.42
73.31	73.31	73.32	73.32	73.32	73.32	73.32	73.32	73.32	73.32	73.32	73.32	73.32	73.32	73.31	73.31
66.21	66.21	66.21	66.21	66.21	66.21	66.21	66.21	66.21	66.21	66.21	66.21	66.21	66.21	66.21	66.21
59.10	59.10	59.10	59.10	59.10	59.10	59.10	59.10	59.10	59.10	59.10	59.10	59.10	59.10	59.10	59.10
51.99	51.99	51.99	51.99	51.99	51.99	51.99	51.99	51.99	51.99	51.99	51.99	51.99	51.99	51.99	51.99
44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88
37.77	37.77	37.77	37.77	37.77	37.77	37.77	37.77	37.77	37.77	37.77	37.77	37.77	37.77	37.77	37.77
30.66	30.66	30.66	30.66	30.66	30.66	30.66	30.66	30.66	30.66	30.66	30.66	30.66	30.66	30.66	30.66
23.55	23.55	23.55	23.55	23.55	23.55	23.55	23.55	23.55	23.55	23.55	23.55	23.55	23.55	23.55	23.55

TABLE 3.3

The angle of the incident radiation is 0 degrees with insolation of 900 Watts per metre squared.
The efficiency of the collector is 16.13% and the ambient temperature is 20.00degrees centigrade.
DT/E = 0.337

20.09	20.16	20.47	20.47	20.52	20.56	20.58	20.59	20.59	20.58	20.56	20.52	20.47	20.47	20.17	20.09
23.72	23.14	21.30	24.06	24.95	25.31	25.48	25.56	25.56	25.48	25.32	24.95	24.06	21.31	23.15	23.73
31.42	30.96	30.17	31.97	33.02	33.63	33.97	34.13	34.13	33.98	33.64	33.04	31.99	30.19	30.98	31.44
39.59	39.13	38.08	40.40	41.33	42.01	42.44	42.65	42.65	42.45	42.02	41.35	40.43	38.12	39.17	39.62
48.22	47.89	47.22	48.67	49.71	50.47	50.96	51.20	51.21	50.97	50.49	49.75	48.72	47.26	47.94	48.26
57.18	57.01	56.82	57.07	58.24	59.07	59.61	59.87	59.88	59.62	59.10	58.29	57.13	56.88	57.06	57.23
66.30	66.14	65.89	65.68	66.98	67.86	68.41	68.69	68.69	68.43	67.89	67.03	65.75	65.95	66.20	66.36
75.59	75.37	74.93	74.23	76.03	76.86	77.41	77.68	77.69	77.43	76.90	76.09	74.31	75.00	75.44	75.65
85.09	84.84	84.23	82.87	85.28	86.04	86.59	86.87	86.87	86.61	86.08	85.34	82.95	84.30	84.90	85.16
94.85	94.65	94.26	93.83	94.40	95.33	95.94	96.25	96.26	95.97	95.38	94.47	93.90	94.33	94.72	94.92
104.81	104.65	104.35	104.03	103.89	104.88	105.53	105.85	105.86	105.56	104.92	103.96	104.09	104.42	104.71	104.88
114.94	114.78	114.48	114.08	113.66	114.69	115.36	115.70	115.71	115.39	114.74	113.73	114.14	114.54	114.84	115.00
125.22	125.05	124.71	124.21	123.60	124.80	125.47	125.81	125.82	125.50	124.85	123.67	124.28	124.77	125.11	125.28
135.67	135.48	135.10	134.46	133.47	135.27	135.86	136.16	136.17	135.88	135.31	133.54	134.52	135.16	135.54	135.72
146.30	146.13	145.74	145.05	143.77	145.95	146.47	146.75	146.75	146.49	145.99	143.84	145.11	145.80	146.18	146.35
157.11	156.98	156.69	156.23	155.54	156.71	157.26	157.54	157.55	157.28	156.74	155.59	156.28	156.74	157.02	157.16
168.05	167.98	167.83	167.64	167.51	167.74	168.28	168.55	168.56	168.30	167.77	167.54	167.68	167.87	168.02	168.09
179.06	179.05	179.02	178.98	178.97	178.99	179.51	179.78	179.78	179.53	179.01	179.00	179.02	179.05	179.08	179.10
190.09	190.13	190.21	190.31	190.41	190.45	190.96	191.22	191.22	190.97	190.48	190.44	190.34	190.24	190.16	190.12
201.08	201.18	201.37	201.63	201.90	202.10	202.61	202.86	202.87	202.62	202.12	201.92	201.65	201.40	201.21	201.11
211.96	212.14	212.48	212.93	213.44	213.90	214.47	214.72	214.72	214.49	213.92	213.46	212.96	212.50	212.17	211.99
222.66	222.94	223.46	224.19	225.03	225.89	226.56	226.76	226.77	226.57	225.92	225.05	224.21	223.49	222.96	222.69
233.09	233.49	234.26	235.32	236.59	237.93	238.78	238.98	238.98	238.79	237.95	236.62	235.35	234.28	233.51	233.11
243.12	243.67	244.75	246.26	248.09	250.05	251.14	251.35	251.35	251.15	250.08	248.12	246.28	244.77	243.69	243.14
252.59	253.34	254.79	256.88	259.47	262.32	263.66	263.89	263.89	263.66	262.34	259.49	256.90	254.81	253.35	252.61
261.31	262.29	264.21	267.01	270.57	274.64	276.35	276.62	276.62	276.36	274.65	270.59	267.03	264.23	262.30	261.33
269.07	270.29	272.74	276.39	281.16	286.80	289.25	289.59	289.59	289.25	286.81	281.17	276.40	272.76	270.31	269.08
275.59	277.08	280.07	284.65	290.87	298.76	302.44	302.86	302.86	302.44	298.77	290.88	284.66	280.09	277.09	275.61
280.64	282.34	285.83	291.26	298.93	309.44	316.11	316.53	316.53	316.11	309.45	298.94	291.27	285.84	282.35	280.65
283.97	285.83	289.64	295.62	304.16	316.10	323.54	323.54	323.54	323.54	316.10	304.17	295.62	289.65	285.84	283.98
285.46	287.37	291.28	297.41	305.99	317.16	323.55	323.55	323.55	323.55	317.16	306.00	297.41	291.29	287.37	285.46
285.03	286.89	290.73	296.74	305.25	316.61	323.55	323.55	323.55	323.55	316.61	305.25	296.74	290.73	286.90	285.03
282.73	284.45	287.99	293.56	301.66	313.57	323.55	323.55	323.55	323.55	313.57	301.66	293.56	287.99	284.46	282.74
278.72	280.20	283.22	287.85	294.25	302.47	311.78	314.07	314.07	311.78	302.48	294.25	287.85	283.22	280.20	278.72
273.21	274.42	276.82	280.39	285.01	290.31	295.24	297.43	297.43	295.24	290.31	285.01	280.39	276.82	274.42	273.22
266.51	267.44	269.26	271.88	275.09	278.51	281.44	282.97	282.97	281.44	278.51	275.09	271.88	269.26	267.44	266.51
258.88	259.57	260.90	262.76	264.97	267.20	269.04	270.05	270.05	269.04	267.20	264.97	262.76	260.90	259.57	258.88
250.56	251.05	252.00	253.31	254.81	256.29	257.48	258.14	258.14	257.48	256.29	254.81	253.31	252.01	251.05	250.56
241.73	242.09	242.76	243.66	244.68	245.67	246.45	246.88	246.88	246.45	245.67	244.68	243.66	242.76	242.09	241.74
232.56	232.81	233.27	233.89	234.59	235.25	235.77	236.05	236.05	235.77	235.25	234.59	233.89	233.27	232.81	232.56
223.14	223.31	223.63	224.06	224.53	224.97	225.32	225.51	225.51	225.32	224.97	224.53	224.06	223.63	223.31	223.14
213.54	213.66	213.88	214.17	214.49	214.79	215.02	215.15	215.15	215.03	214.79	214.49	214.17	213.88	213.66	213.54
203.83	203.91	204.06	204.26	204.48	204.68	204.84	204.92	204.92	204.84	204.68	204.48	204.26	204.06	203.91	203.83
194.04	194.10	194.20	194.33	194.48	194.62	194.72	194.78	194.78	194.72	194.62	194.48	194.33	194.20	194.10	194.04
184.19	184.23	184.30	184.39	184.49	184.58	184.66	184.69	184.69	184.66	184.58	184.49	184.39	184.30	184.23	184.19
174.31	174.33	174.38	174.44	174.51	174.57	174.62	174.65	174.65	174.62	174.57	174.51	174.44	174.38	174.33	174.31
164.39	164.41	164.44	164.49	164.53	164.58	164.61	164.63	164.63	164.61	164.58	164.53	164.49	164.44	164.41	164.39
154.47	154.48	154.50	154.53	154.56	154.59	154.61	154.62	154.62	154.61	154.59	154.56	154.53	154.50	154.48	154.47
144.52	144.53	144.55	144.57	144.59	144.61	144.62	144.63	144.63	144.62	144.61	144.59	144.57	144.55	144.53	144.52
134.58	134.58	134.59	134.60	134.62	134.63	134.64	134.65	134.65	134.64	134.63	134.62	134.60	134.59	134.58	134.58
124.62	124.62	124.63	124.64	124.65	124.66	124.67	124.67	124.67	124.67	124.66	124.65	124.64	124.63	124.62	124.62
114.66	114.66	114.67	114.68	114.68	114.69	114.69	114.70	114.70	114.69	114.69	114.68	114.68	114.67	114.66	114.66
104.70	104.70	104.71	104.71	104.71	104.72	104.72	104.72	104.72	104.72	104.72	104.71	104.71	104.71	104.70	104.70
94.74	94.74	94.74	94.74	94.75	94.75	94.75	94.75	94.75	94.75	94.75	94.75	94.75	94.74	94.74	94.74
84.78	84.78	84.78	84.78	84.78	84.78	84.78	84.79	84.79	84.78	84.78	84.78	84.78	84.78	84.78	84.78
74.81	74.81	74.81	74.81	74.81	74.82	74.82	74.82	74.82	74.82	74.82	74.81	74.81	74.81	74.81	74.81
64.85	64.85	64.85	64.85	64.85	64.85	64.85	64.85	64.85	64.85	64.85	64.85	64.85	64.85	64.85	64.85
54.88	54.88	54.88	54.88	54.88	54.88	54.88	54.88	54.88	54.88	54.88	54.88	54.88	54.88	54.88	54.88
44.91	44.91	44.91	44.92	44.92	44.92	44.92	44.92	44.92	44.92	44.92	44.92	44.92	44.91	44.91	44.91
34.95	34.95	34.95	34.95	34.95	34.95	34.95	34.95	34.95	34.95	34.95	34.95	34.95	34.95	34.95	34.95
24.98	24.98	24.98	24.98	24.98	24.98	24.98	24.98	24.98	24.98	24.98	24.98	24.98	24.98	24.98	24.98

TABLE 3.4

DATA FILE: MATTEMP.DAT THE STEADY STATE TEMPERATURE DISTRIBUTION

The angle of the incident radiation is 0 degrees with insolation of 900 Watts per metre squared.
The efficiency of the collector is 0.00% and the ambient temperature is 20.00degrees centigrade.

DT/E = 0.434

20.11	20.20	20.56	20.56	20.63	20.68	20.70	20.71	20.71	20.70	20.68	20.63	20.56	20.56	20.20	20.12
24.58	23.86	21.57	24.93	26.03	26.48	26.70	26.79	26.79	26.70	26.49	26.04	24.94	21.57	23.86	24.59
34.08	33.47	32.41	34.65	35.96	36.73	37.16	37.36	37.36	37.16	36.74	35.98	34.67	32.43	33.49	34.10
44.20	43.58	42.16	45.06	46.23	47.09	47.64	47.90	47.90	47.65	47.11	46.26	45.09	42.20	43.61	44.23
54.93	54.48	53.56	55.32	56.65	57.61	58.24	58.55	58.55	58.25	57.64	56.68	55.36	53.60	54.53	54.97
66.12	65.87	65.55	65.78	67.28	68.35	69.03	69.37	69.38	69.05	68.38	67.33	65.84	65.61	65.92	66.17
77.55	77.31	76.91	76.55	78.22	79.35	80.06	80.42	80.42	80.08	79.38	78.27	76.62	76.98	77.37	77.61
89.23	88.92	88.28	87.28	89.59	90.65	91.36	91.72	91.73	91.39	90.69	89.65	87.36	88.35	88.98	89.29
101.21	100.85	100.01	98.18	101.24	102.22	102.93	103.29	103.30	102.95	102.26	101.30	98.26	100.08	100.92	101.28
113.56	113.27	112.72	112.08	112.75	113.96	114.75	115.14	115.15	114.77	114.00	112.82	112.15	112.79	113.34	113.62
126.19	125.95	125.52	125.01	124.77	126.04	126.89	127.31	127.31	126.91	126.09	124.83	125.08	125.58	126.02	126.25
139.06	138.83	138.39	137.79	137.16	138.50	139.37	139.81	139.82	139.40	138.55	137.23	137.86	138.45	138.89	139.12
152.16	151.91	151.42	150.69	149.80	151.36	152.23	152.66	152.67	152.26	151.41	149.87	150.76	151.48	151.97	152.22
165.50	165.24	164.68	163.77	162.37	164.71	165.47	165.86	165.87	165.49	164.75	162.45	163.83	164.74	165.30	165.56
179.11	178.86	178.30	177.32	175.54	178.33	179.02	179.38	179.39	179.04	178.37	175.61	177.38	178.36	178.91	179.17
192.98	192.78	192.35	191.66	190.65	192.08	192.83	193.20	193.21	192.85	192.11	190.70	191.71	192.40	192.83	193.03
207.05	206.92	206.67	206.32	206.02	206.20	206.96	207.33	207.34	206.97	206.23	206.05	206.36	206.71	206.96	207.09
221.24	221.19	221.09	220.94	220.79	220.67	221.41	221.78	221.79	221.43	220.70	220.82	220.97	221.12	221.23	221.28
235.49	235.51	235.54	235.57	235.56	235.46	236.19	236.55	236.56	236.20	235.49	235.59	235.60	235.57	235.54	235.53
249.72	249.82	250.00	250.22	250.44	250.54	251.27	251.64	251.64	251.28	250.56	250.46	250.25	250.03	249.85	249.75
263.85	264.05	264.41	264.90	265.41	265.84	266.68	267.04	267.04	266.70	265.87	265.44	264.93	264.44	264.07	263.88
277.78	278.10	278.71	279.54	280.48	281.40	282.43	282.74	282.75	282.44	281.43	280.51	279.57	278.74	278.13	277.81
291.39	291.87	292.80	294.07	295.56	297.09	298.42	298.72	298.73	298.43	297.12	295.59	294.10	292.82	291.89	291.41
304.51	305.20	306.53	308.39	310.61	312.96	314.65	314.97	314.97	314.65	312.98	310.64	308.41	306.55	305.22	304.53
316.95	317.89	319.72	322.34	325.55	329.06	331.15	331.50	331.50	331.15	329.08	325.57	322.36	319.74	317.91	316.97
328.45	329.69	332.13	335.69	340.18	345.29	347.94	348.35	348.35	347.94	345.30	340.20	335.70	332.15	329.70	328.46
338.71	340.28	343.42	348.10	354.21	361.40	365.07	365.57	365.57	365.07	361.41	354.22	348.12	343.44	340.30	338.72
347.39	349.31	353.18	359.10	367.14	377.29	382.66	383.27	383.27	382.66	377.30	367.15	359.11	353.19	349.32	347.40
354.16	356.37	360.90	367.96	377.95	391.63	400.96	401.54	401.54	400.96	391.64	377.96	367.97	360.91	356.38	354.17
358.71	361.13	366.10	373.90	385.07	400.71	410.95	410.95	410.95	410.95	400.71	385.08	373.91	366.10	361.13	358.71
360.84	363.33	368.45	376.47	387.73	402.44	410.96	410.96	410.96	410.96	402.44	387.73	376.47	368.46	363.34	360.84
360.47	362.91	367.92	375.79	386.94	401.85	410.96	410.96	410.96	410.96	401.85	386.94	375.79	367.93	362.91	360.47
357.66	359.91	364.53	371.82	382.40	397.96	410.95	410.95	410.95	410.95	397.96	382.40	371.82	364.54	359.92	357.67
352.61	354.55	358.49	364.54	372.89	383.62	395.71	398.70	398.70	395.71	383.62	372.89	364.55	358.49	354.55	352.61
345.61	347.18	350.32	354.98	361.01	367.91	374.33	377.18	377.18	374.33	367.91	361.01	354.98	350.32	347.19	345.61
337.04	338.26	340.63	344.05	348.24	352.70	356.51	358.51	358.51	356.51	352.70	348.24	344.05	340.63	338.26	337.05
327.26	328.16	329.90	332.33	335.21	338.12	340.52	341.83	341.83	340.52	338.12	335.21	332.34	329.90	328.17	327.27
316.59	317.24	318.48	320.18	322.14	324.07	325.61	326.47	326.47	325.62	324.07	322.14	320.18	318.48	317.24	316.59
305.26	305.72	306.59	307.77	309.10	310.38	311.40	311.96	311.96	311.40	310.39	309.10	307.77	306.59	305.72	305.26
293.47	293.79	294.39	295.21	296.11	296.97	297.65	298.02	298.02	297.65	296.97	296.11	295.21	294.40	293.79	293.47
281.35	281.58	281.99	282.55	283.16	283.74	284.19	284.44	284.44	284.19	283.74	283.16	282.55	281.99	281.58	281.35
269.01	269.17	269.46	269.84	270.25	270.64	270.95	271.11	271.11	270.95	270.64	270.25	269.84	269.46	269.17	269.02
256.52	256.63	256.83	257.08	257.37	257.63	257.83	257.95	257.95	257.83	257.63	257.37	257.08	256.83	256.63	256.52
243.93	244.00	244.13	244.31	244.50	244.68	244.82	244.89	244.89	244.82	244.68	244.50	244.31	244.13	244.00	243.93
231.26	231.31	231.40	231.52	231.65	231.77	231.86	231.91	231.91	231.86	231.77	231.65	231.52	231.40	231.31	231.26
218.54	218.57	218.63	218.72	218.80	218.89	218.95	218.98	218.98	218.95	218.89	218.80	218.72	218.63	218.57	218.54
205.79	205.81	205.85	205.91	205.97	206.02	206.06	206.09	206.09	206.06	206.02	205.97	205.91	205.85	205.81	205.79
193.01	193.03	193.06	193.09	193.13	193.17	193.20	193.22	193.22	193.20	193.17	193.13	193.09	193.06	193.03	193.01
180.22	180.23	180.25	180.28	180.30	180.33	180.35	180.36	180.36	180.35	180.33	180.30	180.28	180.25	180.23	180.22
167.42	167.43	167.44	167.46	167.48	167.49	167.51	167.51	167.51	167.51	167.49	167.48	167.46	167.44	167.43	167.42
154.61	154.62	154.63	154.64	154.65	154.66	154.67	154.68	154.68	154.67	154.66	154.65	154.64	154.63	154.62	154.61
141.80	141.80	141.81	141.82	141.83	141.83	141.84	141.84	141.84	141.84	141.83	141.83	141.82	141.81	141.80	141.80
128.98	128.99	128.99	128.99	129.00	129.01	129.01	129.01	129.01	129.01	129.01	129.00	128.99	128.99	128.99	128.98
116.16	116.17	116.17	116.17	116.18	116.18	116.18	116.18	116.18	116.18	116.18	116.18	116.17	116.17	116.17	116.16
103.34	103.35	103.35	103.35	103.35	103.35	103.35	103.36	103.36	103.36	103.36	103.35	103.35	103.35	103.35	103.34
90.52	90.52	90.53	90.53	90.53	90.53	90.53	90.53	90.53	90.53	90.53	90.53	90.53	90.53	90.52	90.52
77.70	77.70	77.70	77.70	77.71	77.71	77.71	77.71	77.71	77.71	77.71	77.71	77.70	77.70	77.70	77.70
64.88	64.88	64.88	64.88	64.88	64.88	64.88	64.88	64.88	64.88	64.88	64.88	64.88	64.88	64.88	64.88
52.06	52.06	52.06	52.06	52.06	52.06	52.06	52.06	52.06	52.06	52.06	52.06	52.06	52.06	52.06	52.06
39.23	39.23	39.23	39.23	39.23	39.24	39.24	39.24	39.24	39.24	39.24	39.24	39.23	39.23	39.23	39.23
26.41	26.41	26.41	26.41	26.41	26.41	26.41	26.41	26.41	26.41	26.41	26.41	26.41	26.41	26.41	26.41

TABLE 3.5

6. Repeat for different heat losses.
7. Create the required matrices.
8. Create the finite difference equations.
9. Write the matrices out to file for futher processing.
10. Call the subroutine SOLMAT.FOR to solve and output the temperature distribution.

The structure diagram for this program is shown at Fig.3.13.

The subroutine SOLMAT.FOR can likewise be itemized as follows:-

1. Read the matrices in the data files MATA.DAT and MATB.DAT.
2. Evaluate the temperature distribution using F04ATF.
3. Write the solution array to data file MATTEMP.DAT.

During the development of these programs it was necessary to construct a program that could analyse the contents of the matrices. The program INSPEC__MAT.FOR was written which could diplay any row of the coeffient matrices.

There are two procedures required for this routine namely:-

1. Read the data files MATA.DAT and MATB.DAT.
2. Write the requested row to data file TEMP.DAT.

To help clarify the program sequence required to simulate the steady state temperature distribution the operations flowchart is shown at Fig.3.14.

THE FINITE DIFFERENCE LINEAR EQUATIONS:

To evaluate the finite difference equations it will be assumed that the top and bottom of the collector are prescribed temperature boundaries and the left and right sides are prescribed heat flux boundaries where by symmetry it is assumed that there is no heat flow because nodes on either side of the boundary are at the same temperature. There are therefore five cases to consider, the four exterior node cases plus the case of an internal node. The general form of the finite difference

STRUCTURE DIAGRAM FOR FINITE DIFFERENCES PROGRAM (FINDIF.FOR)

This program creates the finite difference linear equations for the temperature distribution network.

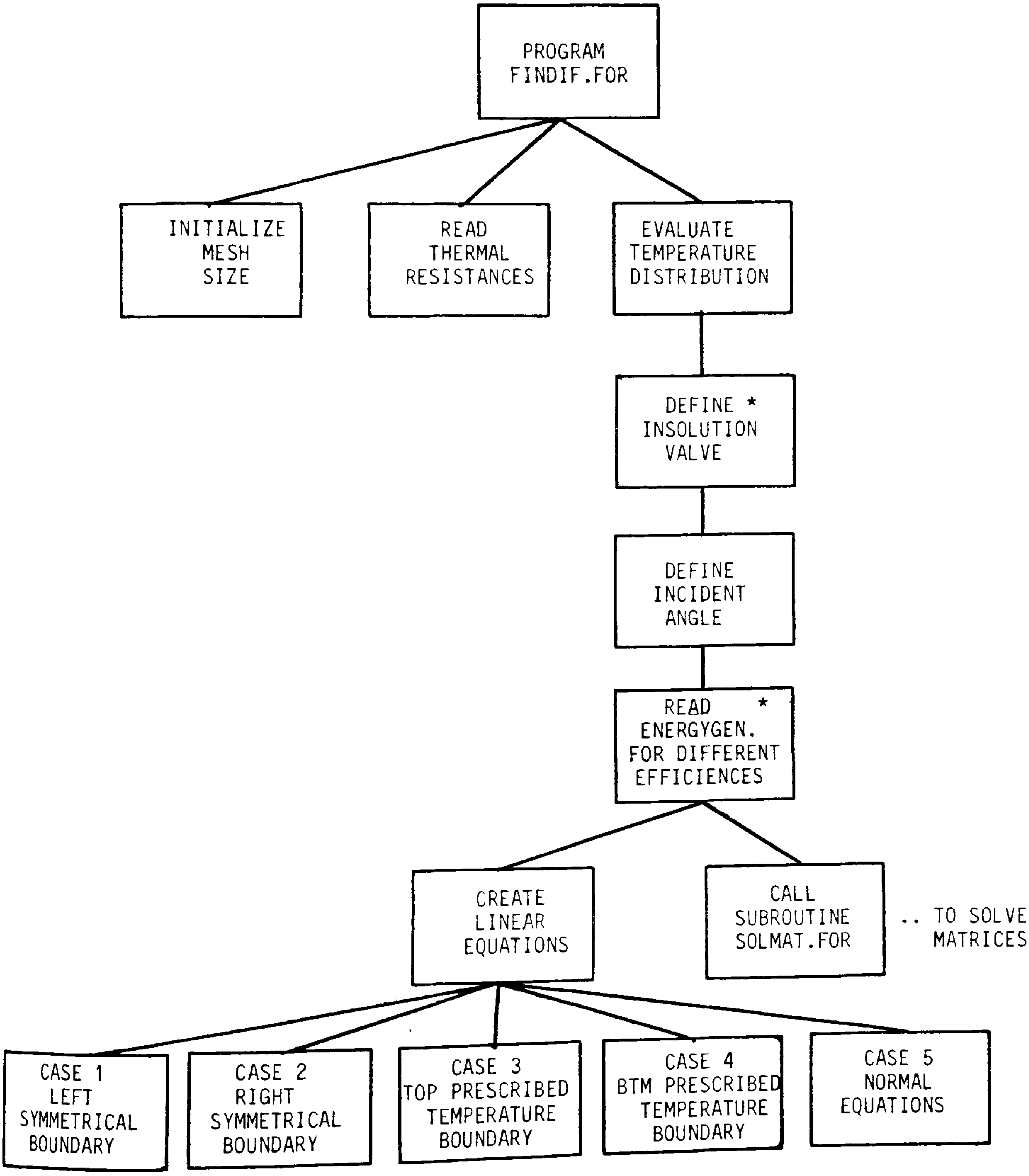


Fig.3.13

THE OPERATIONS FLOWCHART FOR THE STEADY STATE TEMPERATURE DISTRIBUTION

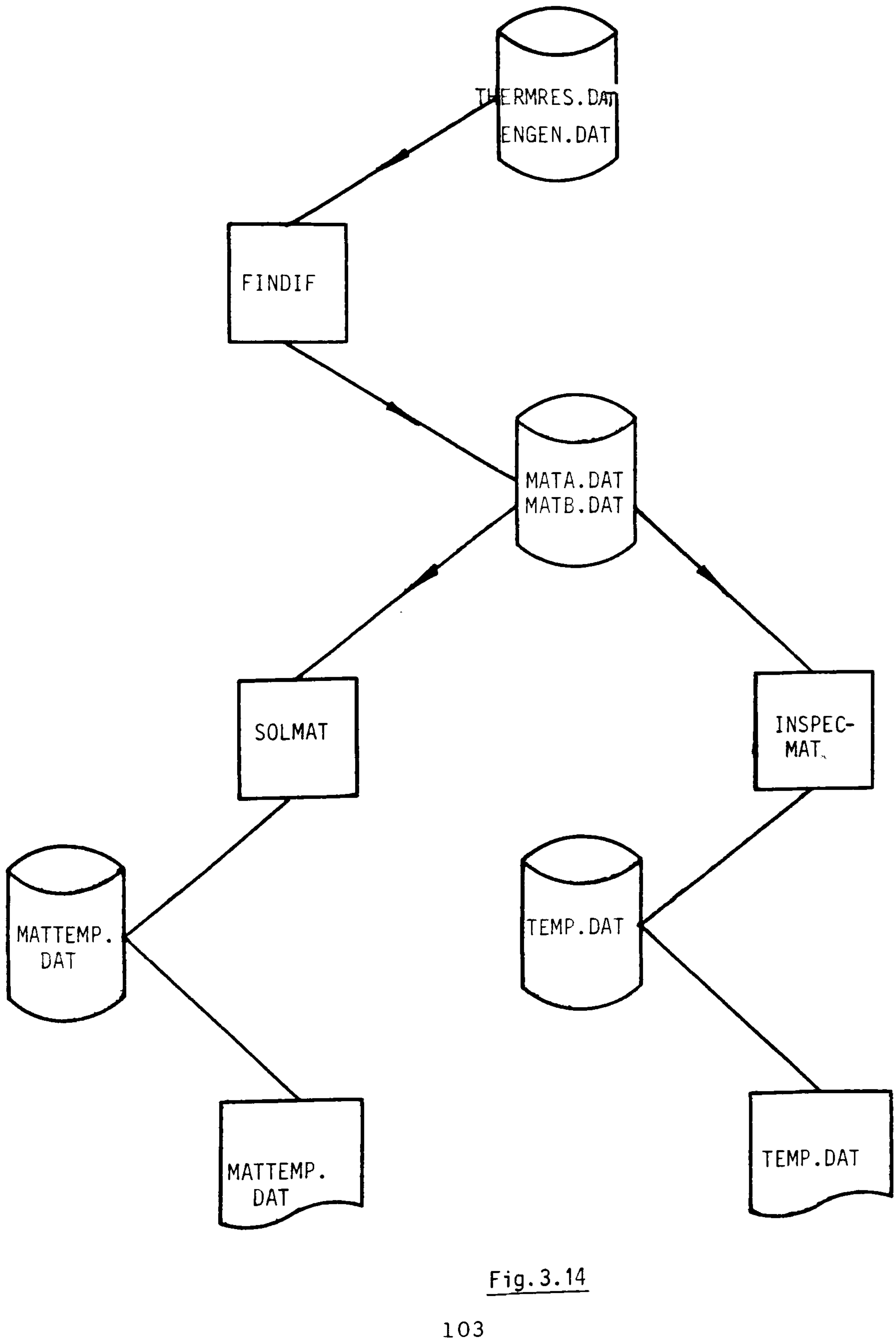
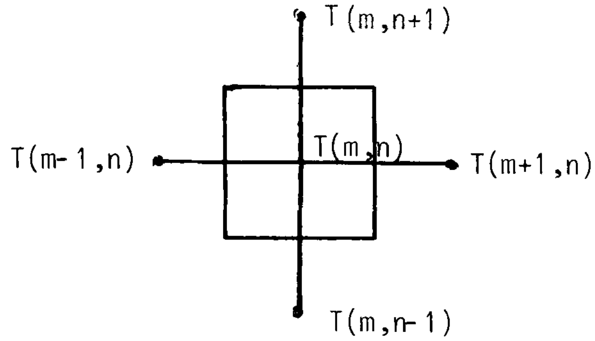


Fig. 3.14

equation in terms of thermal resistances was given in section 3.2 and is rearranged for the mesh coordinate system for the element with the temperature node $T_{(m,n)}$ as follows:-

<u>THE ELEMENT (m,n) WITH ITS FOUR NEIGHBOURING NODES</u>



$$[T_{(m-1,n)} - T_{(m,n)}]/R(m-1,n,1)$$

$$+ \quad [T_{(m+1,n)} - T_{(m,n)}]/R(m,n,1)$$

$$+ \quad [T_{(m,n-1)} - T_{(m,n)}]/R(m,n-1,2)$$

$$+ \quad [T_{(m,n+1)} - T_{(m,n)}]/R(m,n,2)$$

$$+ \quad L^2G(m,n)$$

$$= 0$$

This must be slightly modified for the four boundary cases.

<u>CASE 1</u>

Where MI is the initial horizontal boundary

IF M-1 < MI THEN

$$[T_{(m-1,n)} - T_{(m,n)}]/R(m-1,n,1) = 0$$

<u>CASE 2</u>

Where MF is the final horizonal boundary

IF M+1 > MF THEN

$[T_{(m+1,n)} - T_{(m,n)}]/R(m,n,1) = 0$

CASE 3

Where NI is the initial vertical boundary and TAM the ambient temperature.

IF N-1 < NI THEN

$[T_{(m,n-1)} - T_{(m,n)}]/R(m,n-1,2)$ is replaced with

$[TAM - T_{(m,n)}]/R(m,n-1,2)$

CASE 4

Where NF is the final vertical boundary

IF N+1 > NF THEN

$[T_{(m,n+1)} - T_{(m,n)}]/R(m,n,2)$ is replaced with

$[TAM - T_{(m,n)}]/R(m,n,2)$

To enable the coeffients of the temperature nodes to be located in the correct position in the coefficient matrix it is necessary to map the elemental coordinate system onto the rows and columns of the matrix. This can be achieved once the number of elements has been decided therefore where the number of horizontal and vertical nodes are MF and NF respectively the corresponding row T and the position T in each row of the coefficient of $T_{(m,n)}$ is given by:-

T = (n-NI)*MF+m

therefore C(m,n) the coefficient of the node T(m,n) when considering the element (m,n) is mapped onto A(T,T) of the coefficient matrix and the four neighbouring nodes are mapped as follows:-

C(m-1,n) ---> A(T-1,T)

C(m+1,n) ---> A(T+1,T)

C(m,n-1) ---> A(T-MF,T)

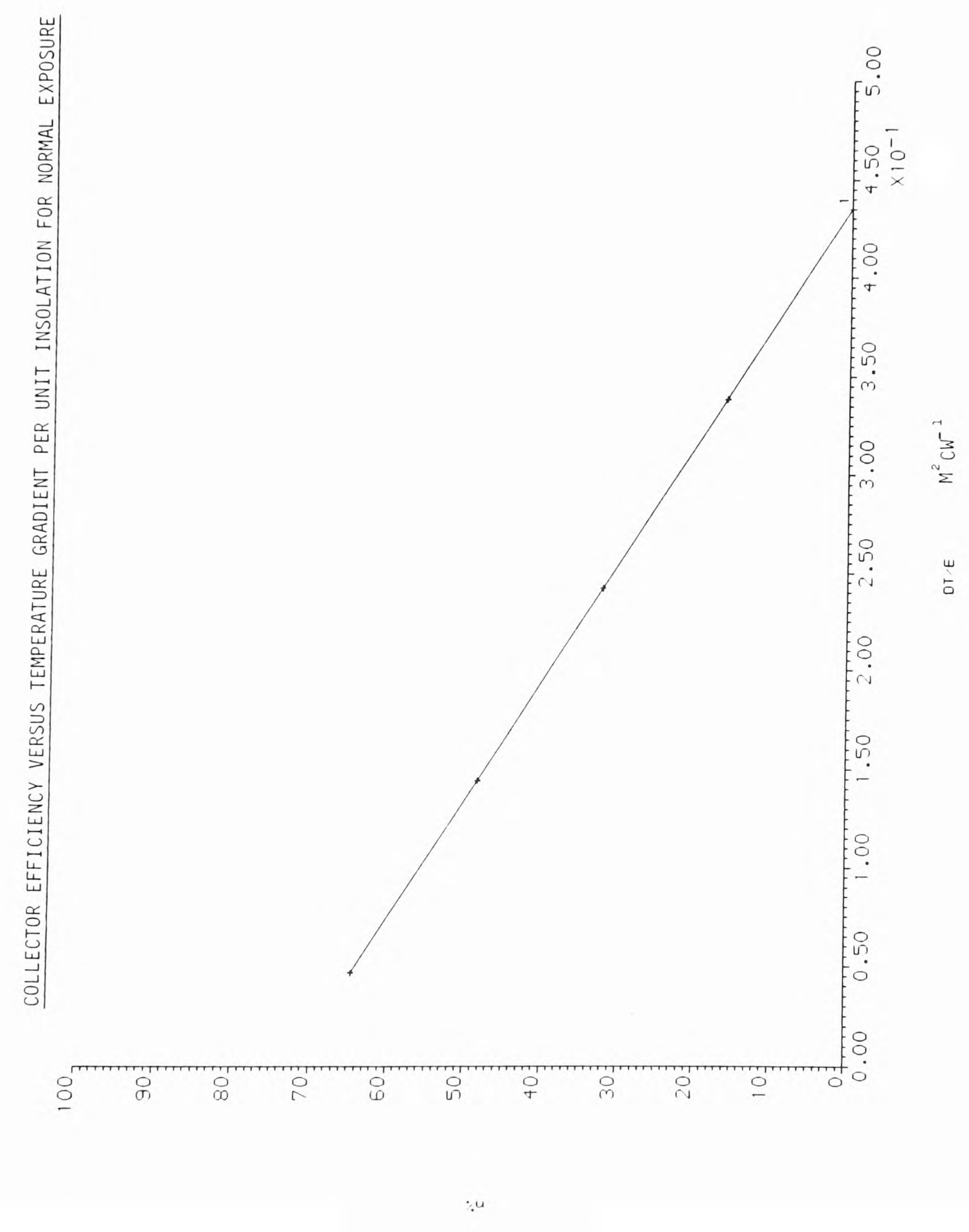
C(m,n+1) ---> A(T+MF,T)

3.5.1 THE SIMULATION OF EFFICIENCY VERSUS DIFERENTIAL TEMPERATURE PER UNIT INSOLATION

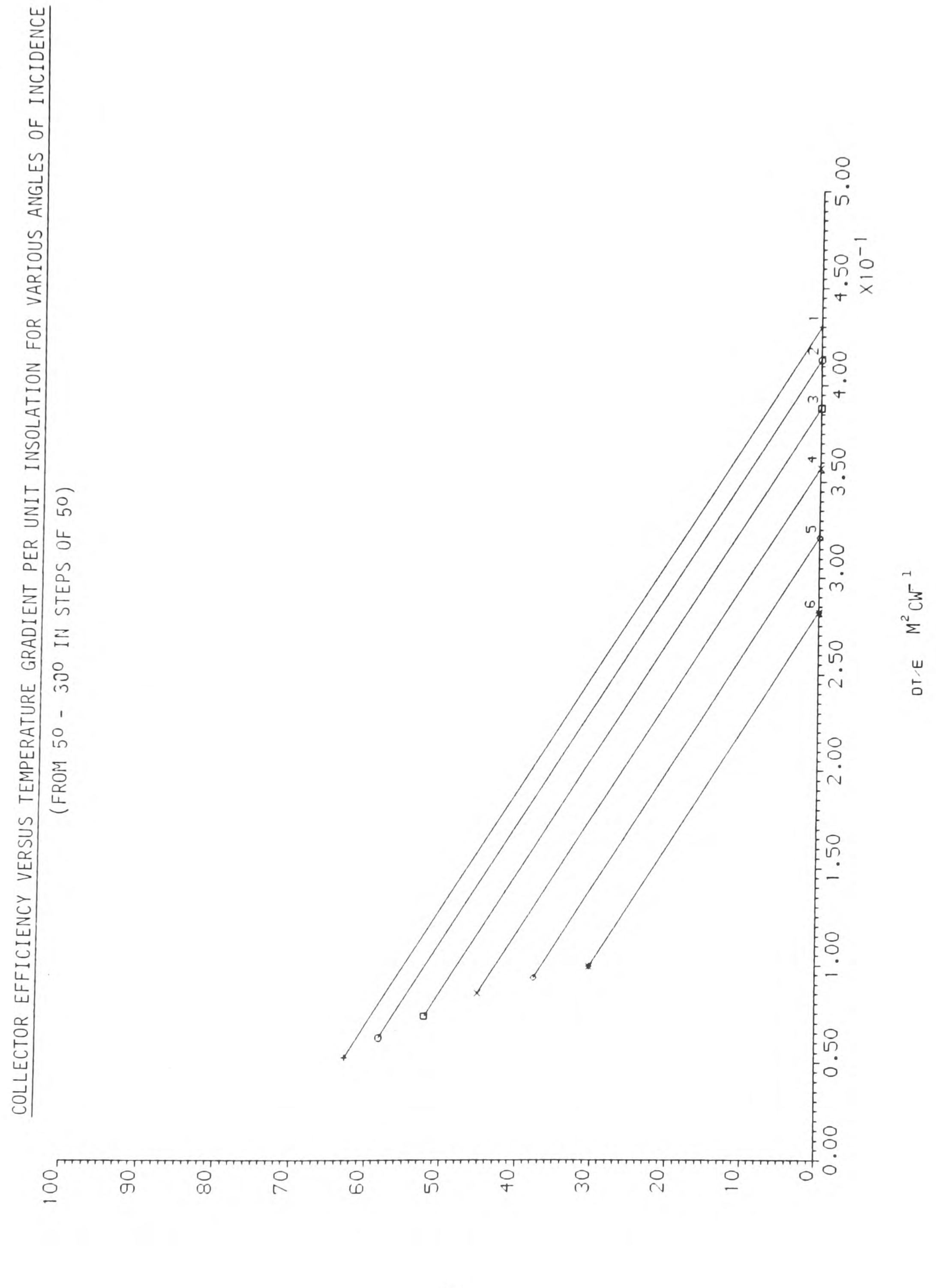
From the steady state temperature distributions it is possible to plot the graphs of efficiency against the temperature rise per unit insolation for various angles of incident radiation. GRAPH 3.1 shows the graph for normal beam radiation on the collector. The effect of off normal radiation is demonstrated by GRAPH 3.2, the six graphs shown are for angles of incidence of between 5^{o} and 30^{o} in 5^{o} increments. The fall off of efficiency becoming more apparent as the incidence angle increases. This choice of graph demonstrates meaningful efficiencies unaffected by varying insolation levels.

These results predict excellent efficiencies for the chosen collector. They are interesting in that they show the order of magnitude of efficiencies for a collector with the same physical properties as that used in the simulation. (A more involved disscussion on collector efficiencies will be dealt with in chapter 5.)

Of particular interest is the shallow slope of the graphs which correspond to the heat loss coefficient determined in section 2.3. The prediction on that simplistic model was 0.224 but here where heat loss through the insulation and the Hyvis are considered, besides heat generation, the value is some seven times greater at 1.655. However it was pointed out then and justifiably that the earlier heat loss prediction was only to serve as an indication of its order of magnitude.


COLLECTOR EFFICIENCY VERSUS TEMPERATURE GRADIENT PER UNIT INSOLATION FOR NORMAL EXPOSURE
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
X10⁻¹
DT/E
M²CW⁻¹
0
10
20
30
40
50
60
70
80
90
100

Graph 3.1


COLLECTOR EFFICIENCY VERSUS TEMPERATURE GRADIENT PER UNIT INSOLATION FOR VARIOUS ANGLES OF INCIDENCE
(FROM 5° - 30° IN STEPS OF 5°)
0 10 20 30 40 50 60 70 80 90 100
%η
0.00 0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00
X10⁻¹
DT/E M²CW⁻¹
1
2
3
4
5
6

Graph 3.2

3.6 THE UNSTEADY HEAT TRANSFER MODEL

3.6.1 INTRODUCTION

Unsteady heat conduction can be solved numerically by transforming the partial differential equation of heat conduction into finite difference equations in both space and time. There are numerous ways of constructing the finite difference equations and to investigate this aspect of the simulation the explicit method has been adopted with a forward finite difference formulation of the change in temperature with time rather than the implicit method which involves the use of backward difference formulation in time {ref.3.1}. The explicit method leads to a set of uncoupled algebraic equations which are relatively easy to solve however the method can predict unstable results if the time step exceeds a certain value called the stability criterion. This however is not inherent in the implicit scheme but suffers from a set of coupled algebraic equations which for large networks are difficult and tedious to solve.

3.6.2 THE TWO DIMENSIONAL FINITE DIFFERENCE REPRESENTATION OF THE TIME DEPENDANT HEAT CONDUCTION EQUATION

Consider the Fourier two dimensional time dependant heat conduction equation {ref.3.1} with heat generation given in the form:-

$$k\left[\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2}\right] + g(x,y) = p\ C\ \frac{dT}{dt}$$

where

k = thermal conductivity

g(x,y) = the energy generation at the position (x,y) p = the density

C = the capacitance

T = the temperature

For the finite difference method it is possible to include the effects of heat capacitance by considering a time dependant energy balance equation for the volume element associated with the temperature node under consideration. This equation can be stated as:-

{Rate of heat entering DV from all its surfaces at time step i } + {Rate of energy generation in DV at time step i } = {Rate of increase of internal energy of DV }

In terms of thermal resistances and using forward difference formulation with time the energy balance equation becomes:-

for j=1 to 4 and for the element with temperature node T_z

$$\left[\frac{T_j - T_z}{R_{jz}}\right] + V_z g_z = pC_z DV_z \left[\frac{T_z^{\,i} - T_z^{\,i+1}}{Dt}\right]$$

This equation can be rearranged to give the explicit form of the forward temperature node $T_z^{\,i+1}$ as follows:-

for j = 1 to 4

$$T_z^{\,i+1} = \frac{Dt}{M_z C_z}\left\{\left[\frac{T_j - T_z}{R_{jz}}\right] + V_z g_z\right\} + T_z^{\,i}$$

where the elemental side is L and

R_{jz} = $\{L/KA\}_{jz}$ the thermal resistance between nodes j and z

V_z the volume of the element about node z

g_z the energy generation rate per unit volume at node z

The boundary conditions required for the collector are prescribed temperature for the top and bottom surfaces and adiabatic for the sides. At a prescribed temperature boundary the actual temperature of the neighbouring node is substituted into the equation while at an adiabatic boundary the temperature of the neighbouring node is given the same temperature as the elemental node.

Using the scarbough criterion {ref.3.3} for the time step where

$$Dt < MC/4k$$

the elements of the 0.5cm mesh give the maximum time steps that can be used in the above equations for the materials used for the collector as:-

for the insulation < 22.5 sec

for the Hyvis < 75.0 sec

for the receiver < 0.019 sec

This means that a very small time step must be used in order to achieve stable matrix solutions and since the overall time constant of the system is quite large the routine will have to be repeated over a considerable length of time which makes the solution long winded and tedious.
Before the temperature distributions with respect to time can be evaluated it is necessary to construct a mesh of elemental mass capacitances over the whole region and this with the elemental energy generation and thermal resistance networks already available will enable the uncoupled linear equations to be formulated.

3.7 THE THERMAL CAPACITANCE SYSTEM

3.7.1. INTRODUCTION

As the collector absorbs energy from the sun the temperature of the collector will rise with time and subsequently alter the energy balance within the collector. It is therefore of interest to predict how the temperature of the collector will change with time so as to evaluate the time constant of the collector. To enable this it is necessary to obtain the combined mass capacitance values of each element of the grid and this will be achieved by the program MASCAP.FOR. The thermal properties of all the materials are listed in TABLE 3.6. Once this has been completed the finite difference equations of temperature with time can be obtained.

3.7.2 THE ELEMENTAL MASS CAPACITANCE PROGRAM

The objective is to write a program (MASCAP.FOR) that will evaluate the energy required to raise each element of the mesh through 1C.

The precedures required to complete the program are itemized as follows:-

1. Initialize all the boundaries and mesh size.
2. Read all the thermal capacitances and densities of the materials used in the system.
3. Evaluate all the positive mass capacitances.
4. Map onto symmetrical elements.
5. Evaluate all negative elements.
6. Overwrite for receiver thermal masses.
7. Write to data file. (EJPDC.DAT)

The structure diagram for this program is shown at fig.3.15.

Using the same notation as that used for the energy generation program the different composite elemental mass capacitances are

THE STRUCTURE DIAGRAM FOR THE MASS CAPACITANCE PROGRAM

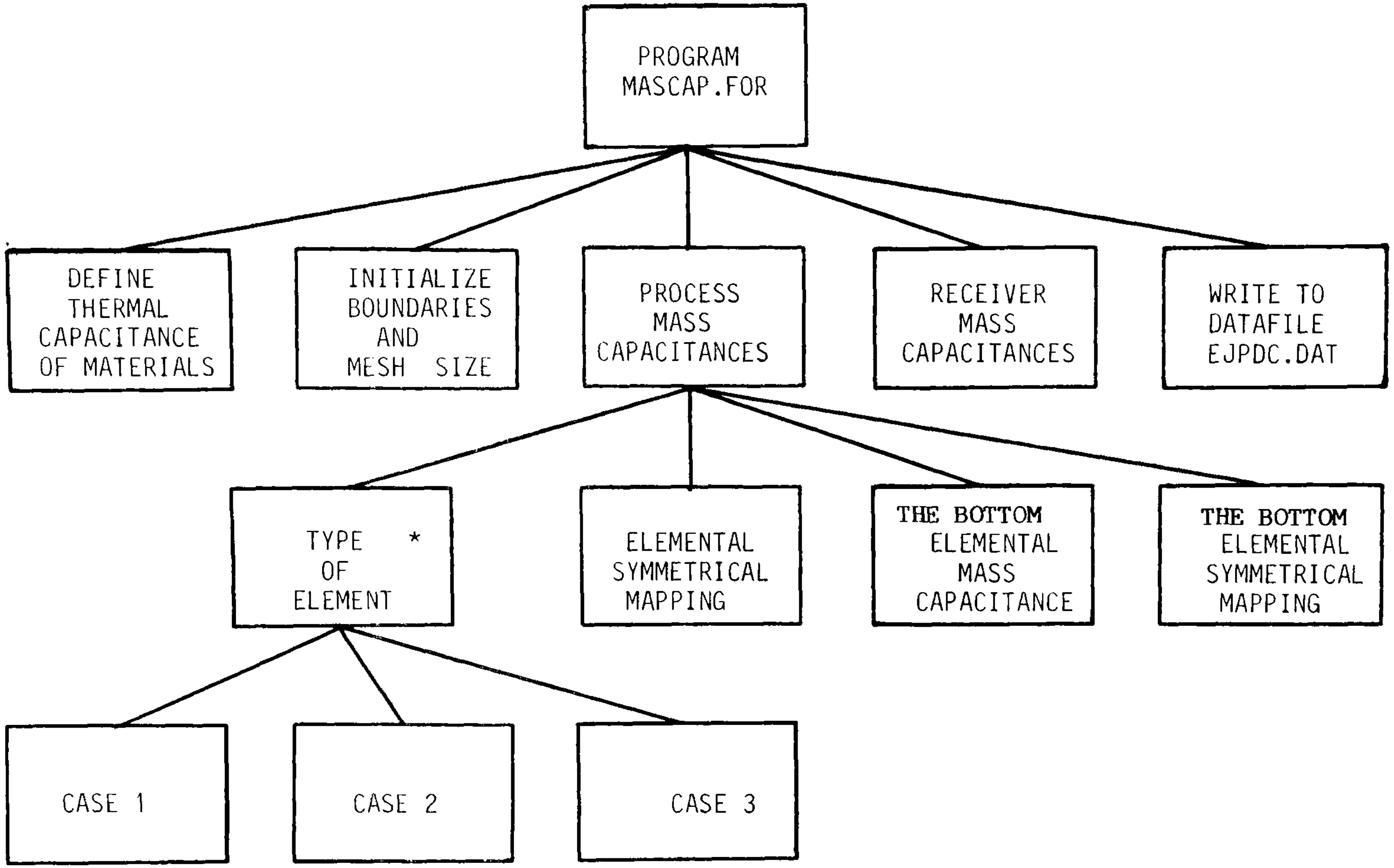


Fig.3.15

as follows:-

CASE 1

The mass capacitance MC for an internal element.

1g. For glass.

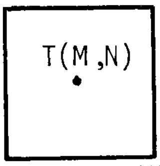
$$MC = L^2 p_g C_g$$

1h. For Hyvis.

$$MC = L^2 p_h C_h$$

1i. For insulation.

$$MC = L^2 p_i C_i$$



NO BOUNDARIES WITHIN ELEMENT

1r. The mass capacitance of the receiver.

The mass capacitance of each element of the receiver was calculated by dividing its total mass capacitance by the number of elements cotained within the receiver. The cross sectional area of each material in the receiver was calculated as:-

Air (inside inner tube)	= 154.0 mm^2
Copper (internal)	= 22.8 mm^2
Water	= 43.8 mm^2
Copper (external)	= 66.0 mm^2
Insulation	= 19.9 mm^2

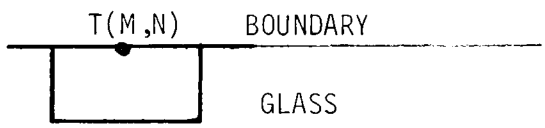
The mass capacitances for each of these materials per unit length using the thermal properties in the TABLE 3.6 is:-

Air	= 0.15 JC^{-1}
Copper (combined)	= 304.53 JC^{-1}
Water	= 181.39 JC^{-1}
Whole receiver (MCR)	= 487.52 JC^{-1}

CASE 2

The mass capacitance MC on a glass air boundary.

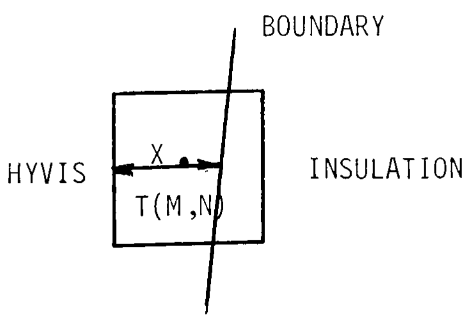
$$MC = (L^2\ p_g\ C_g)/2$$



CASE 3

The mass capacitance MC on a vertical Hyvis to insulation boundary.

$$MC = (L \times p_h\ C_h) + (L(L - x)\ p_i\ C_i)$$



THE THERMAL PROPERTIES OF THE MATERIALS USED

MATERIAL	THERMAL CAPACITANCE $JKg^{-1}C^{-1}$	DENSITY Kgm^{-3}	THERMAL CONDUCTIVITY $Wm^{-1}C^{-1}$	THERMAL DIFFUSIVITY M^2s^{-1}
Insulation foam @30C	1045	70	0.026	
Hyvis @50C	2000	921	0.15	
Glass @30C	837	2500	1.2	0.594×10^{-6}
Water @60C	4184	985	0.651	0.155×10^{-6}
Copper @20C	383	8954	386	112.3×10^{-6}
Air @60C	1006	1.177	0.0262	0.222×10^{-4}

TABLE 3.6

3.8 THE TEMPERATURE VERSUS TIME SIMULATION

3.8.1 THE EXPLICIT TIME DEPENDANT HEAT CONDUCTION EQUATION

Once the elemental mass capacitances have been evaluated it is possible to construct the uncoupled linear equations for the explicit time dependant heat conduction scheme. Here the temperature at time i+1 is evaluated knowing its value at i. The program HETCAP.FOR has been constructed to evaluate the temperature at each node of the network with respect to time.

The procedures required in constructing this program can be itemized as follows:-

1. Define the boundaries,mesh size and time step.
2. Read the data files of energy generation, thermal resistances and mass capacitances.
3. Select stagnation heat loss conditions.
4. Repeat for the required elapsed time.
5. Construct the forward difference linear equations.
6. Create new temperature distribution.
7. Write to data file (TIMETEMP.DAT).

The structure diagram for this program is shown at Fig.3.16.

The output from this program shows the temperature distribution at half hourly intervals. TABLES 3.7-3.9 show the temperatures throughout the collector at 1,3 and 6 hours after being at the ambient temperature. GRAPH 3.3 shows the variation of the receiver temperature over a 12 hour period using a time step of 0.01 seconds. In order to reduce the number of iterations the receiver was removed from the collector thereby allowing a much larger time step. GRAPH 3.4 and 3.5 show the same temperature distributions for a 5 second and 2 second time step for the resulting collector. The time constant for this distribution is 5.25 hours.

STRUCTURE DIAGRAM FOR THE EXPLICIT FINITE DIFFERENCE PROGRAM (HETCAP.FOR)

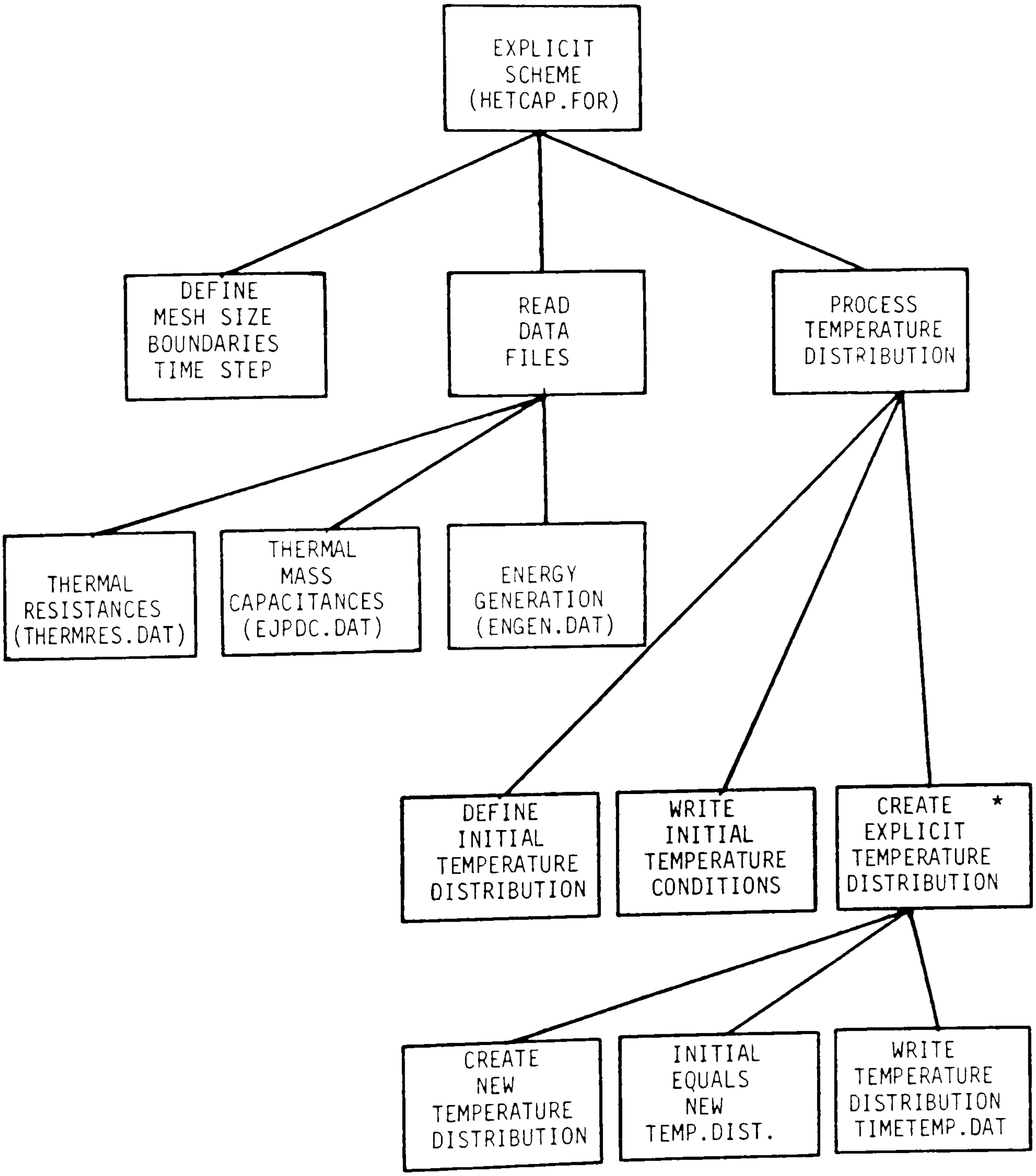


Fig.3.16

The angle of incident radiation is 0 degrees
With insolation of 900 W/m².
The efficiency of the collector is 0.00%
The ambient temperature is 20.00
After 1.00 Hrs the temperature distribution is:-

20.01	20.02	20.07	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.07	20.02	20.01
20.32	20.46	20.84	20.64	20.57	20.53	20.51	20.51	20.51	20.52	20.54	20.57	20.64	20.85	20.47	20.33
20.80	20.97	21.32	21.18	21.08	21.01	20.97	20.95	20.95	20.97	21.02	21.09	21.20	21.34	20.99	20.82
21.13	21.28	21.62	21.50	21.37	21.28	21.22	21.19	21.19	21.23	21.29	21.39	21.53	21.66	21.31	21.16
21.31	21.42	21.60	21.70	21.55	21.43	21.36	21.33	21.33	21.37	21.45	21.58	21.75	21.65	21.46	21.35
21.42	21.50	21.65	21.80	21.63	21.50	21.42	21.38	21.39	21.43	21.53	21.67	21.85	21.70	21.54	21.46
21.47	21.53	21.66	21.82	21.63	21.50	21.42	21.38	21.38	21.43	21.53	21.67	21.87	21.71	21.58	21.51
21.48	21.53	21.64	21.82	21.59	21.47	21.39	21.36	21.36	21.40	21.50	21.63	21.89	21.70	21.58	21.53
21.47	21.51	21.60	21.75	21.57	21.44	21.37	21.35	21.35	21.38	21.48	21.62	21.83	21.66	21.57	21.52
21.46	21.48	21.53	21.58	21.56	21.43	21.35	21.34	21.34	21.37	21.46	21.62	21.64	21.59	21.54	21.51
21.46	21.48	21.51	21.54	21.55	21.42	21.35	21.33	21.33	21.37	21.46	21.61	21.60	21.57	21.54	21.52
21.50	21.51	21.53	21.56	21.58	21.44	21.36	21.33	21.34	21.39	21.48	21.64	21.62	21.59	21.56	21.55
21.56	21.57	21.59	21.62	21.65	21.49	21.41	21.38	21.38	21.43	21.53	21.71	21.68	21.65	21.62	21.61
21.67	21.68	21.70	21.72	21.77	21.57	21.49	21.45	21.46	21.51	21.60	21.84	21.78	21.75	21.73	21.72
21.84	21.84	21.85	21.87	21.90	21.72	21.62	21.57	21.57	21.64	21.75	21.96	21.92	21.90	21.89	21.88
22.08	22.07	22.07	22.05	22.00	21.96	21.79	21.71	21.71	21.81	21.99	22.04	22.09	22.11	22.11	22.12
22.40	22.39	22.37	22.33	22.28	22.26	22.02	21.91	21.92	22.04	22.29	22.31	22.37	22.40	22.43	22.43
22.83	22.82	22.78	22.72	22.63	22.54	22.29	22.16	22.17	22.30	22.56	22.66	22.75	22.81	22.85	22.86
23.41	23.39	23.34	23.25	23.10	22.90	22.63	22.50	22.50	22.65	22.93	23.12	23.28	23.37	23.42	23.44
24.17	24.15	24.09	23.97	23.76	23.43	23.14	22.99	23.00	23.15	23.45	23.78	23.99	24.11	24.17	24.20
25.14	25.12	25.07	24.95	24.71	24.26	23.89	23.74	23.74	23.91	24.28	24.73	24.98	25.10	25.15	25.16
26.35	26.36	26.35	26.28	26.06	25.63	25.02	24.85	24.86	25.03	25.66	26.08	26.30	26.38	26.38	26.38
27.84	27.89	27.97	28.00	27.88	27.47	26.71	26.54	26.54	26.72	27.50	27.90	28.02	27.99	27.91	27.86
29.59	29.73	29.96	30.19	30.28	30.02	29.18	29.02	29.02	29.19	30.04	30.30	30.21	29.98	29.75	29.61
31.60	31.87	32.34	32.92	33.42	33.58	32.73	32.60	32.60	32.74	33.60	33.44	32.93	32.36	31.88	31.62
33.79	34.23	35.06	36.18	37.39	38.33	37.69	37.61	37.61	37.69	38.35	37.40	36.19	35.08	34.25	33.81
36.05	36.72	38.01	39.88	42.15	44.44	44.44	44.44	44.44	44.44	44.45	42.16	39.89	38.03	36.73	36.06
38.22	39.14	40.98	43.78	47.54	52.12	53.46	53.61	53.61	53.46	52.13	47.55	43.79	40.99	39.15	38.23
40.09	41.24	43.63	47.39	52.84	60.51	65.29	65.55	65.55	65.29	60.51	52.85	47.40	43.63	41.25	40.10
41.45	42.79	45.57	50.04	56.67	66.49	73.11	73.11	73.11	73.11	66.49	56.68	50.04	45.58	42.80	41.46
42.16	43.58	46.54	51.27	58.12	67.43	73.11	73.11	73.11	73.11	67.43	58.12	51.27	46.55	43.59	42.16
42.14	43.56	46.48	51.16	57.92	67.21	73.11	73.11	73.11	73.11	67.21	57.92	51.16	46.49	43.56	42.15
41.43	42.73	45.43	49.72	56.03	65.34	73.11	73.11	73.11	73.11	65.34	56.03	49.72	45.43	42.73	41.43
40.10	41.22	43.50	47.03	51.90	58.14	64.98	66.67	66.67	64.98	58.14	51.90	47.03	43.51	41.22	40.10
38.33	39.23	41.03	43.70	47.16	51.12	54.75	56.36	56.36	54.75	51.12	47.16	43.70	41.03	39.23	38.33
36.30	36.98	38.32	40.26	42.63	45.15	47.31	48.43	48.43	47.31	45.15	42.63	40.26	38.33	36.98	36.30
34.17	34.67	35.64	37.00	38.61	40.23	41.58	42.31	42.31	41.58	40.23	38.61	37.00	35.64	34.67	34.17
32.08	32.43	33.12	34.06	35.15	36.20	37.06	37.54	37.54	37.06	36.20	35.15	34.06	33.12	32.44	32.08
30.13	30.37	30.85	31.49	32.21	32.91	33.47	33.78	33.78	33.47	32.91	32.21	31.49	30.85	30.37	30.13
28.36	28.53	28.86	29.29	29.77	30.24	30.60	30.80	30.80	30.60	30.24	29.77	29.29	28.86	28.53	28.36
26.81	26.92	27.15	27.44	27.76	28.07	28.31	28.44	28.44	28.31	28.07	27.76	27.44	27.15	26.93	26.81
25.47	25.56	25.70	25.90	26.11	26.32	26.47	26.56	26.56	26.47	26.32	26.11	25.90	25.70	25.56	25.48
24.35	24.41	24.51	24.64	24.78	24.91	25.02	25.08	25.08	25.02	24.91	24.78	24.64	24.51	24.41	24.35
23.43	23.46	23.53	23.61	23.71	23.80	23.86	23.90	23.90	23.86	23.80	23.71	23.61	23.53	23.46	23.43
22.67	22.69	22.74	22.79	22.86	22.91	22.96	22.98	22.98	22.96	22.91	22.86	22.79	22.74	22.69	22.67
22.05	22.07	22.10	22.14	22.18	22.22	22.25	22.26	22.26	22.25	22.22	22.18	22.14	22.10	22.07	22.05
21.57	21.58	21.60	21.62	21.65	21.68	21.70	21.71	21.71	21.70	21.68	21.65	21.62	21.60	21.58	21.57
21.19	21.19	21.21	21.22	21.24	21.26	21.27	21.28	21.28	21.27	21.26	21.24	21.22	21.21	21.19	21.19
20.89	20.90	20.91	20.92	20.93	20.94	20.95	20.95	20.95	20.95	20.94	20.93	20.92	20.91	20.90	20.89
20.66	20.67	20.67	20.68	20.69	20.69	20.70	20.70	20.70	20.70	20.69	20.69	20.68	20.67	20.67	20.66
20.49	20.49	20.50	20.50	20.51	20.51	20.51	20.52	20.52	20.51	20.51	20.51	20.50	20.50	20.49	20.49
20.36	20.36	20.36	20.37	20.37	20.37	20.37	20.38	20.38	20.37	20.37	20.37	20.37	20.36	20.36	20.36
20.26	20.26	20.26	20.26	20.26	20.27	20.27	20.27	20.27	20.27	20.27	20.26	20.26	20.26	20.26	20.26
20.18	20.18	20.18	20.18	20.18	20.19	20.19	20.19	20.19	20.19	20.19	20.18	20.18	20.18	20.18	20.18
20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13
20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09	20.09
20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05
20.03	20.03	20.03	20.03	20.03	20.03	20.03	20.03	20.03	20.03	20.03	20.03	20.03	20.03	20.03	20.03
20.01	20.01	20.01	20.01	20.01	20.01	20.01	20.01	20.01	20.01	20.01	20.01	20.01	20.01	20.01	20.01
20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00

Table 3.7

DATA FILE: TTIMETEMP.DAT

THE UNSTEADY STATE TEMPERATURE DISTRIBUTION

The angle of incident radiation is 0 degrees
With insolation of 900 W/m².
The efficiency of the collector is 0.00%
The ambient temperature is 20.00
After 3.00 Hrs the temperature distribution is:-

20.01	20.03	20.08	20.11	20.12	20.12	20.11	20.11	20.11	20.12	20.12	20.12	20.11	20.08	20.03	20.01
20.54	20.69	21.11	20.89	20.82	20.80	20.78	20.78	20.78	20.78	20.80	20.83	20.90	21.12	20.70	20.55
21.42	21.58	21.91	21.83	21.75	21.70	21.67	21.66	21.66	21.68	21.71	21.77	21.85	21.94	21.60	21.44
22.16	22.29	22.57	22.56	22.47	22.40	22.36	22.34	22.34	22.37	22.42	22.50	22.60	22.62	22.33	22.19
22.77	22.85	23.00	23.15	23.03	22.94	22.89	22.86	22.87	22.90	22.97	23.07	23.20	23.05	22.90	22.81
23.32	23.38	23.50	23.63	23.51	23.41	23.35	23.32	23.32	23.36	23.44	23.55	23.68	23.55	23.43	23.37
23.83	23.87	23.95	24.05	23.92	23.82	23.75	23.72	23.72	23.77	23.86	23.97	24.12	24.01	23.93	23.89
24.34	24.36	24.39	24.46	24.28	24.18	24.11	24.07	24.08	24.13	24.22	24.34	24.54	24.46	24.42	24.40
24.87	24.86	24.84	24.80	24.68	24.57	24.49	24.45	24.46	24.52	24.61	24.74	24.88	24.91	24.93	24.94
25.46	25.42	25.34	25.20	25.09	24.97	24.90	24.86	24.87	24.92	25.02	25.15	25.27	25.41	25.49	25.53
26.16	26.09	25.95	25.74	25.53	25.43	25.36	25.33	25.34	25.38	25.47	25.60	25.81	26.02	26.16	26.22
27.00	26.90	26.72	26.43	26.09	25.98	25.91	25.88	25.89	25.94	26.03	26.16	26.50	26.78	26.97	27.06
28.01	27.89	27.66	27.30	26.83	26.70	26.62	26.59	26.60	26.65	26.74	26.90	27.36	27.72	27.96	28.07
29.24	29.10	28.81	28.37	27.78	27.61	27.54	27.50	27.51	27.56	27.65	27.85	28.43	28.87	29.16	29.30
30.73	30.57	30.23	29.71	28.96	28.77	28.68	28.63	28.64	28.70	28.81	29.03	29.77	30.29	30.62	30.78
32.52	32.34	31.97	31.39	30.57	30.25	30.10	30.03	30.03	30.12	30.28	30.61	31.44	32.02	32.39	32.57
34.65	34.45	34.07	33.48	32.68	32.07	31.87	31.78	31.78	31.89	32.09	32.71	33.52	34.11	34.50	34.69
37.15	36.96	36.56	35.94	35.08	34.24	34.04	33.94	33.95	34.05	34.26	35.11	35.97	36.60	37.00	37.19
40.05	39.86	39.46	38.83	37.93	36.90	36.70	36.60	36.61	36.71	36.92	37.96	38.86	39.49	39.89	40.08
43.36	43.19	42.82	42.23	41.34	40.18	39.98	39.87	39.88	39.99	40.20	41.37	42.25	42.85	43.22	43.39
47.11	46.98	46.68	46.17	45.36	44.16	43.93	43.81	43.81	43.94	44.18	45.39	46.19	46.71	47.00	47.14
51.29	51.22	51.05	50.70	50.07	49.05	48.65	48.54	48.55	48.67	49.08	50.10	50.72	51.07	51.25	51.32
55.88	55.90	55.92	55.83	55.50	54.76	54.33	54.24	54.24	54.34	54.78	55.53	55.85	55.94	55.93	55.90
60.78	60.96	61.25	61.57	61.72	61.46	61.09	61.03	61.04	61.10	61.48	61.74	61.59	61.27	60.98	60.80
65.88	66.25	66.94	67.83	68.72	69.30	69.10	69.08	69.08	69.10	69.32	68.74	67.85	66.96	66.27	65.90
70.98	71.61	72.80	74.48	76.42	78.27	78.53	78.59	78.59	78.54	78.29	76.44	74.49	72.82	71.62	71.00
75.93	76.84	78.65	81.31	84.66	88.34	89.48	89.64	89.64	89.48	88.35	84.67	81.32	78.67	76.85	75.94
80.41	81.63	84.11	87.89	93.02	99.43	102.20	102.52	102.52	102.21	99.44	93.03	87.91	84.12	81.64	80.42
84.11	85.62	88.71	93.60	100.63	110.48	117.05	117.44	117.44	117.05	110.49	100.64	93.60	88.72	85.63	84.12
86.77	88.48	92.02	97.67	105.94	117.91	125.96	125.96	125.96	125.96	117.91	105.94	97.67	92.03	88.49	86.78
88.22	90.03	93.75	99.64	108.06	119.28	125.97	125.97	125.97	125.97	119.28	108.06	99.65	93.76	90.03	88.23
88.40	90.18	93.84	99.62	107.89	119.04	125.96	125.96	125.96	125.96	119.05	107.89	99.62	93.84	90.18	88.41
87.33	88.96	92.33	97.64	105.36	116.65	125.96	125.96	125.96	125.96	116.65	105.36	97.64	92.33	88.97	87.33
85.14	86.54	89.39	93.76	99.78	107.43	115.85	117.93	117.93	115.85	107.44	99.78	93.77	89.39	86.55	85.15
82.08	83.21	85.44	88.78	93.08	97.98	102.48	104.47	104.47	102.48	97.99	93.09	88.78	85.44	83.21	82.09
78.35	79.21	80.91	83.34	86.32	89.46	92.14	93.53	93.53	92.14	89.46	86.32	83.34	80.91	79.22	78.35
74.21	74.85	76.08	77.81	79.85	81.91	83.59	84.51	84.51	83.59	81.91	79.85	77.81	76.08	74.85	74.21
69.88	70.34	71.22	72.43	73.81	75.17	76.27	76.87	76.87	76.27	75.17	73.81	72.43	71.22	70.34	69.88
65.55	65.87	66.48	67.32	68.26	69.16	69.88	70.28	70.28	69.88	69.16	68.26	67.32	66.48	65.87	65.55
61.33	61.55	61.98	62.55	63.19	63.79	64.28	64.54	64.54	64.28	63.79	63.19	62.55	61.98	61.55	61.33
57.28	57.44	57.73	58.12	58.55	58.95	59.27	59.45	59.45	59.27	58.95	58.55	58.12	57.73	57.44	57.28
53.46	53.57	53.77	54.04	54.33	54.60	54.81	54.93	54.93	54.81	54.60	54.33	54.04	53.77	53.57	53.46
49.90	49.97	50.11	50.29	50.49	50.67	50.82	50.90	50.90	50.82	50.67	50.49	50.29	50.11	49.97	49.90
46.60	46.65	46.74	46.86	47.00	47.12	47.22	47.27	47.27	47.22	47.12	47.00	46.86	46.74	46.65	46.60
43.57	43.61	43.67	43.75	43.84	43.93	43.99	44.03	44.03	43.99	43.93	43.85	43.75	43.67	43.61	43.57
40.81	40.83	40.88	40.93	41.00	41.05	41.10	41.12	41.12	41.10	41.05	41.00	40.93	40.88	40.83	40.81
38.29	38.31	38.33	38.37	38.42	38.45	38.48	38.50	38.50	38.48	38.45	38.42	38.37	38.33	38.31	38.29
36.01	36.02	36.04	36.07	36.10	36.13	36.15	36.16	36.16	36.15	36.13	36.10	36.07	36.04	36.02	36.01
33.95	33.96	33.97	33.99	34.01	34.03	34.04	34.05	34.05	34.04	34.03	34.01	33.99	33.97	33.96	33.95
32.11	32.12	32.13	32.14	32.15	32.16	32.17	32.18	32.18	32.17	32.16	32.15	32.14	32.13	32.12	32.11
30.46	30.46	30.47	30.48	30.49	30.49	30.50	30.50	30.50	30.50	30.49	30.49	30.48	30.47	30.46	30.46
28.99	28.99	28.99	29.00	29.00	29.01	29.01	29.02	29.02	29.01	29.01	29.00	29.00	28.99	28.99	28.99
27.66	27.66	27.66	27.67	27.67	27.67	27.68	27.68	27.68	27.68	27.67	27.67	27.67	27.66	27.66	27.66
26.46	26.46	26.46	26.47	26.47	26.47	26.47	26.47	26.47	26.47	26.47	26.47	26.47	26.46	26.46	26.46
25.37	25.37	25.38	25.38	25.38	25.38	25.38	25.38	25.38	25.38	25.38	25.38	25.38	25.38	25.37	25.37
24.38	24.38	24.38	24.39	24.39	24.39	24.39	24.39	24.39	24.39	24.39	24.39	24.39	24.38	24.38	24.38
23.47	23.47	23.47	23.47	23.47	23.47	23.47	23.47	23.47	23.47	23.47	23.47	23.47	23.47	23.47	23.47
22.62	22.62	22.62	22.62	22.62	22.62	22.62	22.62	22.62	22.62	22.62	22.62	22.62	22.62	22.62	22.62
21.83	21.83	21.83	21.83	21.83	21.83	21.83	21.83	21.83	21.83	21.83	21.83	21.83	21.83	21.83	21.83
21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08	21.08
20.36	20.36	20.36	20.36	20.36	20.36	20.36	20.36	20.36	20.36	20.36	20.36	20.36	20.36	20.36	20.36

Table 3.8

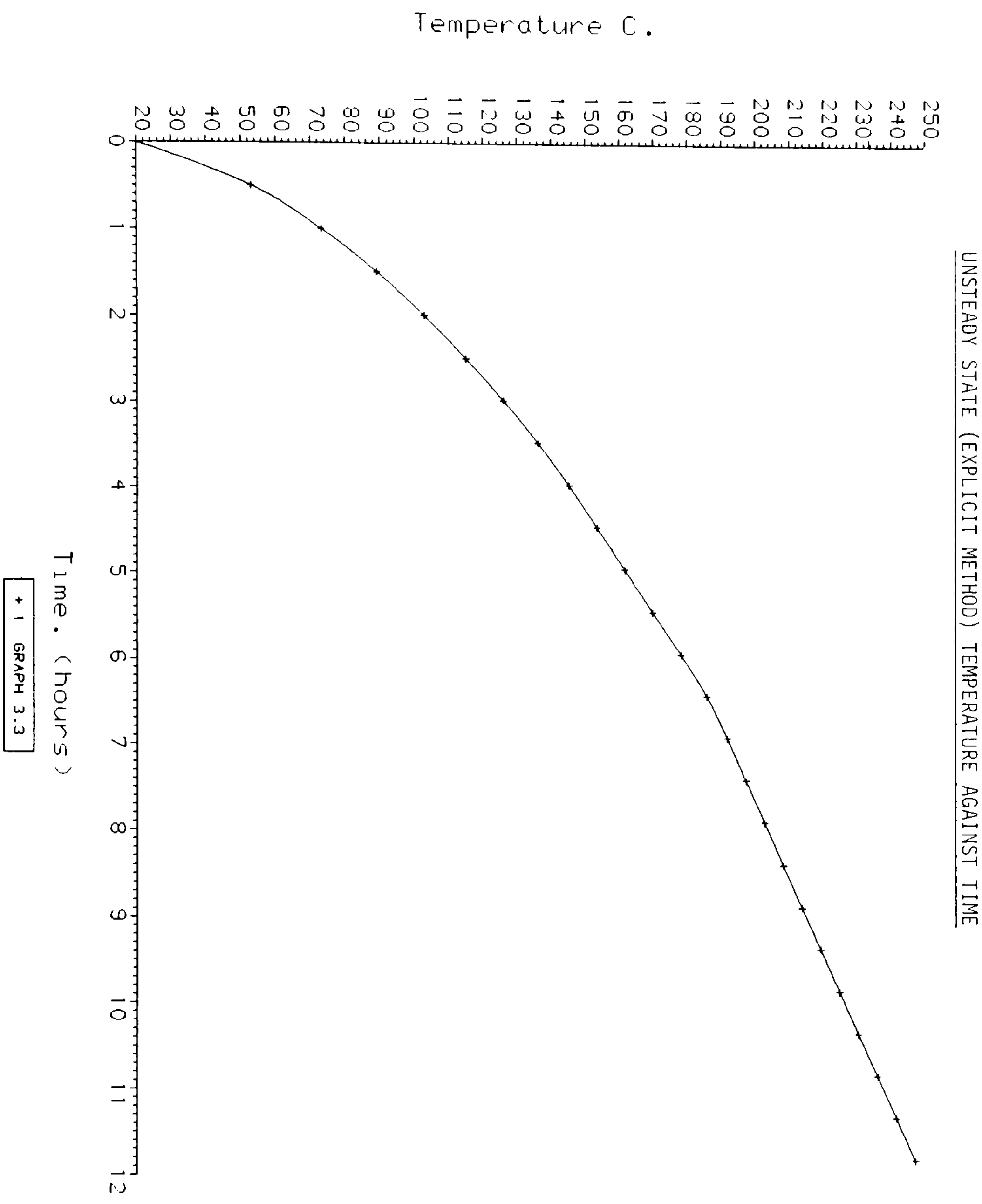
DATA FILE: TIMETEMP.DAT

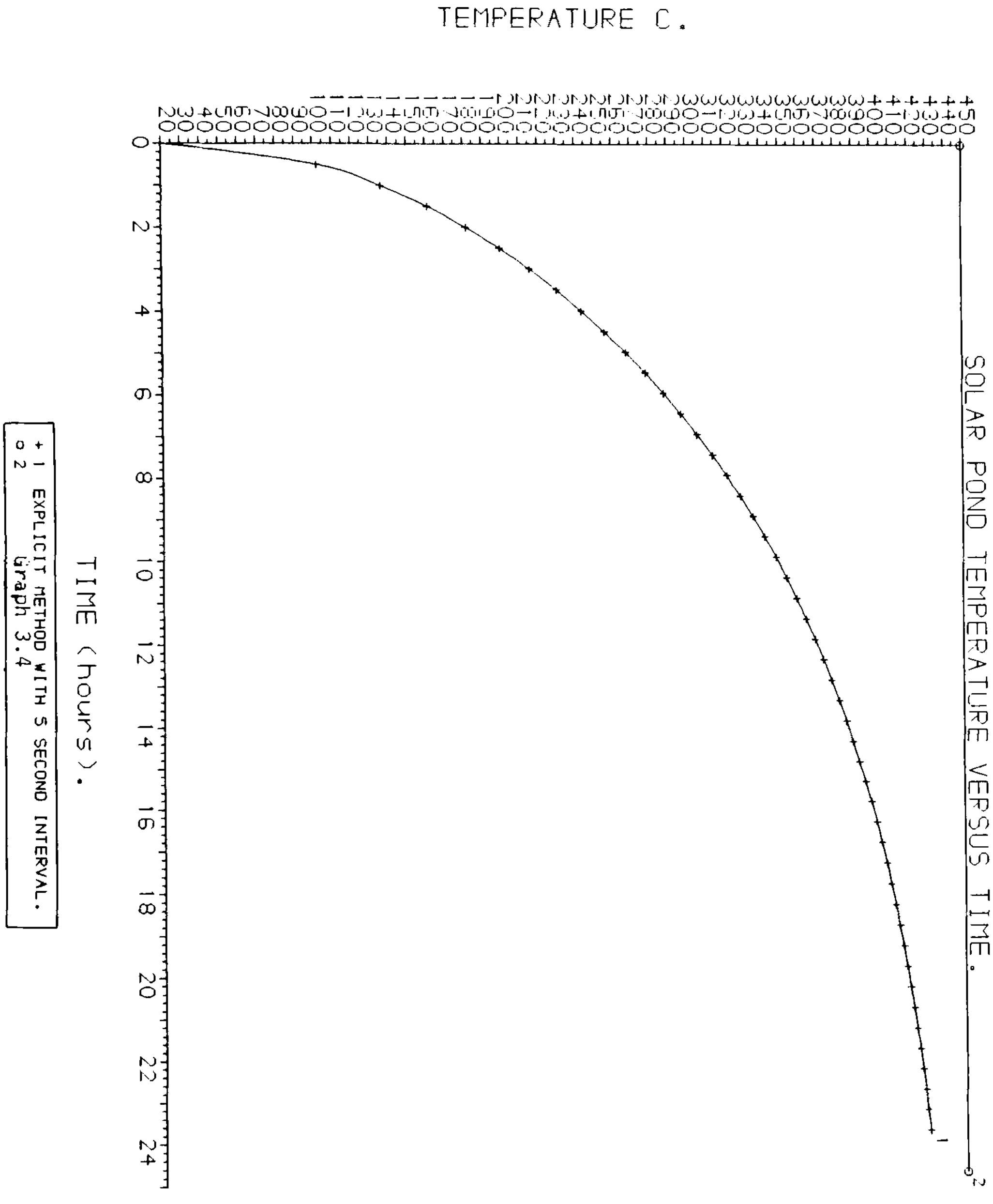
THE UNSTEADY STATE TEMPERATURE DISTRIBUTION

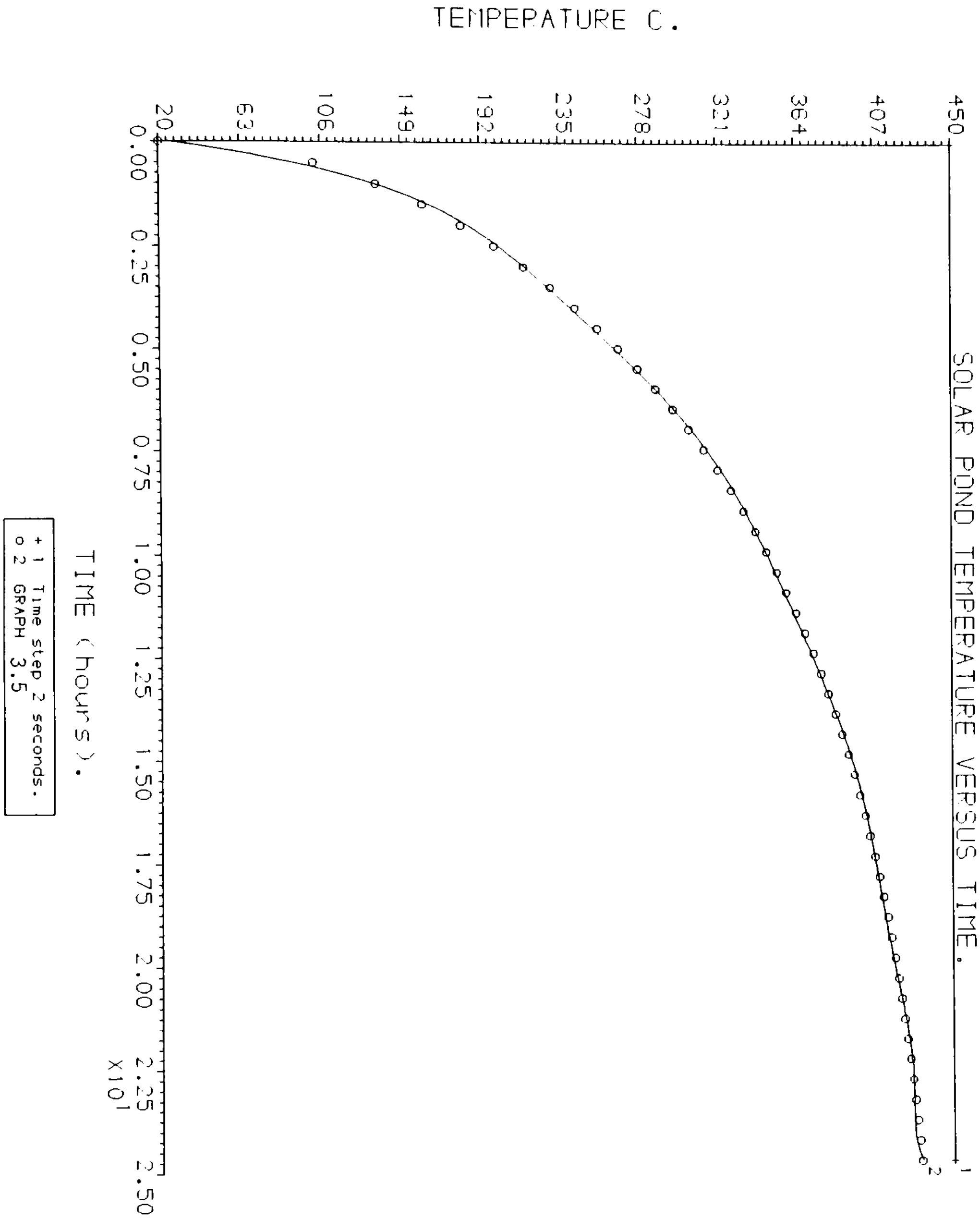
The angle of incident radiation is 0 degrees
With insolation of 900 W/m².
The efficiency of the collector is 0.00%
The ambient temperature is 20.00
After 6.00 Hrs the temperature distribution is:-

20.02	20.04	20.11	20.15	20.16	20.16	20.16	20.16	20.16	20.16	20.16	20.16	20.15	20.11	20.04	20.02
20.95	21.12	21.60	21.35	21.30	21.28	21.27	21.27	21.27	21.28	21.28	21.30	21.36	21.61	21.13	20.96
22.62	22.74	23.00	23.00	22.98	22.96	22.95	22.95	22.95	22.96	22.97	22.99	23.03	23.03	22.77	22.64
24.16	24.22	24.33	24.49	24.46	24.45	24.44	24.44	24.44	24.45	24.47	24.49	24.52	24.38	24.26	24.20
25.68	25.69	25.66	25.88	25.87	25.85	25.85	25.84	25.85	25.86	25.88	25.91	25.93	25.71	25.73	25.73
27.22	27.20	27.19	27.23	27.23	27.21	27.21	27.20	27.21	27.22	27.25	27.27	27.29	27.25	27.26	27.27
28.81	28.76	28.68	28.59	28.61	28.61	28.60	28.60	28.60	28.62	28.64	28.66	28.66	28.75	28.83	28.87
30.49	30.41	30.24	30.00	30.04	30.04	30.04	30.03	30.04	30.06	30.08	30.10	30.08	30.31	30.47	30.55
32.31	32.20	31.94	31.48	31.61	31.60	31.59	31.58	31.59	31.61	31.64	31.67	31.56	32.01	32.26	32.38
34.33	34.19	33.89	33.45	33.24	33.26	33.27	33.28	33.29	33.30	33.31	33.31	33.52	33.96	34.25	34.40
36.59	36.42	36.08	35.57	35.12	35.15	35.17	35.19	35.20	35.20	35.20	35.18	35.64	36.14	36.48	36.65
39.10	38.90	38.51	37.92	37.24	37.27	37.31	37.33	37.34	37.33	37.32	37.31	37.99	38.57	38.97	39.17
41.94	41.71	41.26	40.58	39.68	39.75	39.79	39.82	39.82	39.82	39.80	39.75	40.64	41.32	41.77	42.00
45.12	44.87	44.36	43.57	42.47	42.60	42.64	42.66	42.66	42.66	42.65	42.54	43.64	44.42	44.93	45.17
48.70	48.44	47.88	47.00	45.68	45.85	45.86	45.86	45.87	45.88	45.88	45.75	47.06	47.94	48.49	48.76
52.71	52.45	51.89	51.02	49.79	49.56	49.55	49.54	49.55	49.56	49.59	49.84	51.07	51.94	52.50	52.76
57.17	56.91	56.38	55.57	54.50	53.75	53.70	53.68	53.68	53.71	53.77	54.53	55.61	56.42	56.95	57.21
62.08	61.83	61.33	60.56	59.50	58.48	58.42	58.38	58.39	58.43	58.50	59.53	60.60	61.37	61.87	62.12
67.44	67.22	66.76	66.04	65.00	63.81	63.78	63.77	63.77	63.79	63.84	65.03	66.07	66.80	67.26	67.48
73.28	73.09	72.70	72.06	71.11	69.85	69.84	69.84	69.85	69.86	69.87	71.14	72.09	72.73	73.12	73.31
79.54	79.41	79.13	78.65	77.86	76.67	76.68	76.69	76.69	76.70	76.70	77.89	78.67	79.16	79.44	79.57
86.17	86.13	86.02	85.77	85.26	84.36	84.31	84.31	84.31	84.32	84.39	85.29	85.79	86.05	86.16	86.20
93.13	93.22	93.36	93.46	93.37	92.91	92.93	92.94	92.94	92.94	92.93	93.39	93.48	93.38	93.25	93.16
100.32	100.58	101.06	101.64	102.16	102.37	102.55	102.59	102.59	102.56	102.40	102.19	101.66	101.08	100.60	100.34
107.55	108.04	108.96	110.21	111.58	112.80	113.23	113.30	113.30	113.23	112.82	111.60	110.23	108.98	108.06	107.57
114.61	115.37	116.85	118.96	121.47	124.08	125.00	125.15	125.15	125.00	124.10	121.49	118.97	116.87	115.39	114.63
121.22	122.30	124.44	127.60	131.66	136.25	138.13	138.40	138.40	138.14	136.26	131.67	127.62	124.46	122.31	121.24
127.14	128.55	131.39	135.74	141.66	149.10	152.66	153.07	153.07	152.66	149.11	141.67	135.75	131.41	128.56	127.15
132.02	133.72	137.19	142.65	150.48	161.41	168.83	169.28	169.28	168.83	161.42	150.49	142.66	137.20	133.73	132.03
135.56	137.45	141.36	147.55	156.56	169.51	178.18	178.18	178.18	178.18	169.51	156.57	147.56	141.36	137.46	135.57
137.55	139.52	143.58	149.97	159.05	171.09	178.19	178.19	178.19	178.19	171.09	159.06	149.98	143.59	139.53	137.56
137.93	139.86	143.82	150.06	158.94	170.86	178.19	178.19	178.19	178.19	170.86	158.94	150.06	143.82	139.86	137.93
136.73	138.50	142.13	147.85	156.14	168.23	178.18	178.19	178.19	178.18	168.23	156.14	147.85	142.13	138.50	136.73
134.10	135.62	138.70	143.42	149.90	158.13	167.19	169.44	169.44	167.19	158.13	149.90	143.43	138.71	135.63	134.11
130.31	131.54	133.98	137.59	142.25	147.53	152.39	154.54	154.54	152.39	147.53	142.25	137.60	133.98	131.54	130.31
125.64	126.59	128.44	131.08	134.31	137.72	140.63	142.14	142.14	140.63	137.72	134.31	131.08	128.44	126.59	125.64
120.41	121.11	122.45	124.32	126.53	128.77	130.61	131.61	131.61	130.61	128.77	126.53	124.32	122.45	121.11	120.42
114.87	115.37	116.31	117.61	119.11	120.58	121.77	122.42	122.42	121.77	120.58	119.11	117.61	116.31	115.37	114.87
109.15	109.50	110.16	111.06	112.08	113.06	113.84	114.27	114.27	113.84	113.06	112.08	111.07	110.17	109.50	109.15
103.39	103.63	104.10	104.71	105.41	106.06	106.58	106.86	106.86	106.58	106.06	105.41	104.72	104.10	103.63	103.39
97.69	97.86	98.18	98.61	99.08	99.52	99.86	100.05	100.05	99.86	99.52	99.08	98.61	98.18	97.87	97.70
92.14	92.26	92.48	92.77	93.09	93.39	93.62	93.74	93.74	93.62	93.39	93.09	92.77	92.48	92.26	92.14
86.79	86.87	87.02	87.22	87.43	87.63	87.79	87.88	87.88	87.79	87.64	87.43	87.22	87.02	86.87	86.79
81.67	81.72	81.83	81.96	82.11	82.24	82.35	82.41	82.41	82.35	82.24	82.11	81.96	81.83	81.72	81.67
76.74	76.77	76.84	76.94	77.03	77.13	77.20	77.24	77.24	77.20	77.13	77.03	76.94	76.84	76.77	76.74
72.01	72.04	72.08	72.15	72.21	72.28	72.32	72.35	72.35	72.32	72.28	72.21	72.15	72.08	72.04	72.01
67.50	67.52	67.55	67.60	67.64	67.68	67.72	67.73	67.73	67.72	67.68	67.64	67.60	67.55	67.52	67.50
63.22	63.24	63.26	63.29	63.32	63.35	63.37	63.38	63.38	63.37	63.35	63.32	63.29	63.26	63.24	63.22
59.16	59.17	59.18	59.20	59.22	59.24	59.26	59.26	59.26	59.26	59.24	59.22	59.20	59.18	59.17	59.16
55.28	55.28	55.29	55.31	55.32	55.33	55.34	55.35	55.35	55.34	55.33	55.32	55.31	55.29	55.28	55.28
51.58	51.59	51.59	51.60	51.61	51.62	51.63	51.63	51.63	51.63	51.62	51.61	51.60	51.59	51.59	51.58
48.04	48.04	48.05	48.05	48.06	48.07	48.07	48.07	48.07	48.07	48.07	48.06	48.05	48.05	48.04	48.04
44.65	44.65	44.66	44.66	44.67	44.67	44.67	44.67	44.67	44.67	44.67	44.67	44.66	44.66	44.65	44.65
41.41	41.41	41.41	41.41	41.42	41.42	41.42	41.42	41.42	41.42	41.42	41.42	41.41	41.41	41.41	41.41
38.28	38.29	38.29	38.29	38.29	38.29	38.29	38.29	38.29	38.29	38.29	38.29	38.29	38.29	38.29	38.28
35.28	35.28	35.28	35.28	35.29	35.29	35.29	35.29	35.29	35.29	35.29	35.29	35.28	35.28	35.28	35.28
32.37	32.37	32.37	32.37	32.37	32.37	32.37	32.37	32.37	32.37	32.37	32.37	32.37	32.37	32.37	32.37
29.54	29.54	29.54	29.54	29.54	29.54	29.54	29.54	29.54	29.54	29.54	29.54	29.54	29.54	29.54	29.54
26.77	26.77	26.77	26.77	26.77	26.77	26.77	26.77	26.77	26.77	26.77	26.77	26.77	26.77	26.77	26.77
24.04	24.04	24.04	24.04	24.04	24.04	24.04	24.04	24.04	24.04	24.04	24.04	24.04	24.04	24.04	24.04
21.35	21.35	21.35	21.35	21.35	21.35	21.35	21.35	21.35	21.35	21.35	21.35	21.35	21.35	21.35	21.35

Table 3.9


UNSTEADY STATE (EXPLICIT METHOD) TEMPERATURE AGAINST TIME
Temperature C.
20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250
Time. (hours)
0 1 2 3 4 5 6 7 8 9 10 11 12
+ 1 GRAPH 3.3


TEMPERATURE C.
SOLAR POND TEMPERATURE VERSUS TIME.
TIME (hours).
0 2 4 6 8 10 12 14 16 18 20 22 24
+ 1 EXPLICIT METHOD WITH 5 SECOND INTERVAL.
o 2
Graph 3.4


SOLAR POND TEMPERATURE VERSUS TIME.
TEMPERATURE C.
TIME (hours).
20
63
106
149
192
235
278
321
364
407
450
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
x10^1
+ 1 Time step 2 seconds.
o 2 GRAPH 3.5

THE EXPLICIT FINITE DIFFERENCE LINEAR EQUATIONS:

The general form of the linear equation for the energy balance of an element was given in section 3.6.2 and can be rearranged for the mesh coordinate system for the element with the temperature node T(m,n,z). Where T(m,n,1) is the known present temperature of the element (m,n) and T(m,n,2) is the required predicted temperature after the next time step. Dt the time step, MC(m,n) the mass capacitance of the element (m,n), R(m,n,z) the thermal resistance between the nodes under consideration, G(m,n) the energy generation per unit volume at the element (m,n) and L the length of side of the elements in the network.

$$
\begin{aligned}
T(m,n,2) = \frac{Dt}{MC(m,n)} \{ & [T(m-1,n,1) - T(m,n,1)]/R(m-1,n,1) \\
& + [T(m+1,n,1) - T(m,n,1)]/R(m,n,1) \\
& + [T(m,n-1,1) - T(m,n,1)]/R(m,n-1,2) \\
& + [T(m,n+1,1) - T(m,n,1)]/R(m,n,2) \\
& + L^2 G(m,n)\} + T(m,n,1)
\end{aligned}
$$

As with the steady state finite difference equations it will be assumed that the top and bottom of the collector are prescribed temperature boundaries and the left and right sides are prescribed heat flux boundaries where by symmetry it is assumed that there is no heat flow because nodes on either side of the boundary are at the same temperature. There are therefore five cases to consider, the four exterior node cases plus the case of an internal node.

This equation must be slightly modified for the four boundary cases.

<u>CASE 1</u>

Where MI is the initial horizontal boundary

IF M-1 < MI THEN

[T(m-1,n,1) - T(m,n,1)]/R(m-1,n,1) = 0

CASE 2

Where MF is the final horizontal boundary

IF M+1 > MF THEN

[T(m+1,n,1) - T(m,n,1)]/R(m,n,1) = 0

CASE 3

Where NI is the initial vertical boundary and TAM the ambient temperature.

IF N-1 < NI THEN

[T(m,n-1,1) - T(m,n,1)]/R(m,n-1,2) is replaced with

[TAM - T(m,n,1)]/R(m,n-1,2)

CASE 4

Where NF is the final vertical boundary

IF N+1 > NF THEN

[T(m,n+1,1) - T(m,n,1)]/R(m,n,2) is replaced with

[TAM - T(m,n,1)]/R(m,n,2)

The time step used to predict the temperature time variation with this model was 0.01 seconds (see section 3.6.2) because of the influence of the receiver.

If the receiver is removed from the evaluation leaving just the trap then a much more realistic time step could be considered for the subsequent solar trap. Its maximum steady state temperature using FINDIF.FOR has been evaluated as 452C. GRAPH 3.4 shows how the maximum temperature at the bottom of the solar trap increases over a 24 hour period using a 5 second time interval while GRAPH 3.5 with a time step of 2 seconds verifies the resulting distribution.

REFERENCES

3.1 M.Necati Ozisik, Heat Transfer. A Basic Approach.

3.2 J.F.Duffie and W.A.Beckman, Solar Energy Thermal Processes (1974).

3.3 S.V.Patankar, Numerical Heat Transfer and Fluid Flow (1980).

CHAPTER 4

COLLECTOR DESIGN AND CONSTRUCTION

4.1 INTRODUCTION

From the collector optimisation a shape with a flat top and cylindrical reflecting side surfaces has been chosen. This, with the combination of a continuous fluid flow receiver, a Hyvis leak proof container and the necessity for good insulation qualities has lead to a careful and methodical design and construction.

It is reasonable to assume that the working temperature of the water passing through the collector should never reach 100C and that in general it would never require to go above 80C, this to some extent depends on the storage tank capacity and the available insolation. However during the collector filling process the Hyvis is heated to reduce its viscosity, temperatures in the region of 120C could be reached during this pumping operation. We shall neglect the theoretical stagnation temperature of 410C as it is impractical that the Hyvis would exhibit the same physical properties above 140C because of lower viscosity and consequently high convective losses. It is however worth noting that under extreme conditions the collector could reach this temperature after 6 hours of direct insolation. It will therefore be assumed that the maximum temperature required of the manufacturing materials of the collector shall be 140C.

It is further assumed that the transfer fluid will be water and that all pipework for the receiver is copper (see receiver design for more information).

The initial construction and choice of materials for the collector focussed on the side reflecting surfaces. These surfaces need to be highly mirrored, of low thermal conductivity and able to form the required curves. It is envisaged that under mass production a form of induction moulding would be possible but for a single collector under experimental conditions this would be too expensive and time consumming. Stainless steel was also considered for it would form the curved surfaces easily without much need of support, however because of its low reflectance, which after repeated heating and cooling could drop to 0.5, and relatively high thermal conductivity which would halve the collector efficiency, it to was rejected. Aluminium foil also falls short of the limitations because of its high thermal conductivity,even if the foil is very thin the heat loss would still be significant. Ni-chrome could possibly be the best of these choices with a lower thermal conductivity than stainless steel and reflectivity of about 0.7 to solar radiation but even though the heat loss could of been tolerable the cost of the ni-chrome was self prohibiting.

Vacuum metallised surfaces overcome these problems and are also highly reflective. Of those available, polyester or nylon have the highest working temperatures of 160C and 190C respectively, have low thermal conductivities and compared to the metal foil are much cheaper. The availability of these films 1200mm wide solved the problem of the side surfaces. The metalised-polyester film and all the service pipework will need to be supported. An expanding polyurethane foam which is serviceable up to 150C would amply fill this requirment. The whole collector being contained in a weather proof wooden box. This was constructed of marine ply as it is weather resistant and durable, thermally less conducting and cheaper than metal. Fig.4.1.

The end plates of each channel Fig.4.2 could of been made of PTFE sheet this would of amply satisfied the operational conditions but was overcome much cheaper by using nylon sheet 10mm thick to which the receiver pipe and the side surfaces can be sealed.

The number of channels in the test collector was limited to three, this limits the amount of energy being collected but also reduces manufacturing costs and construction time. Fig.4.1. The experimentation could then be carried out either using all three

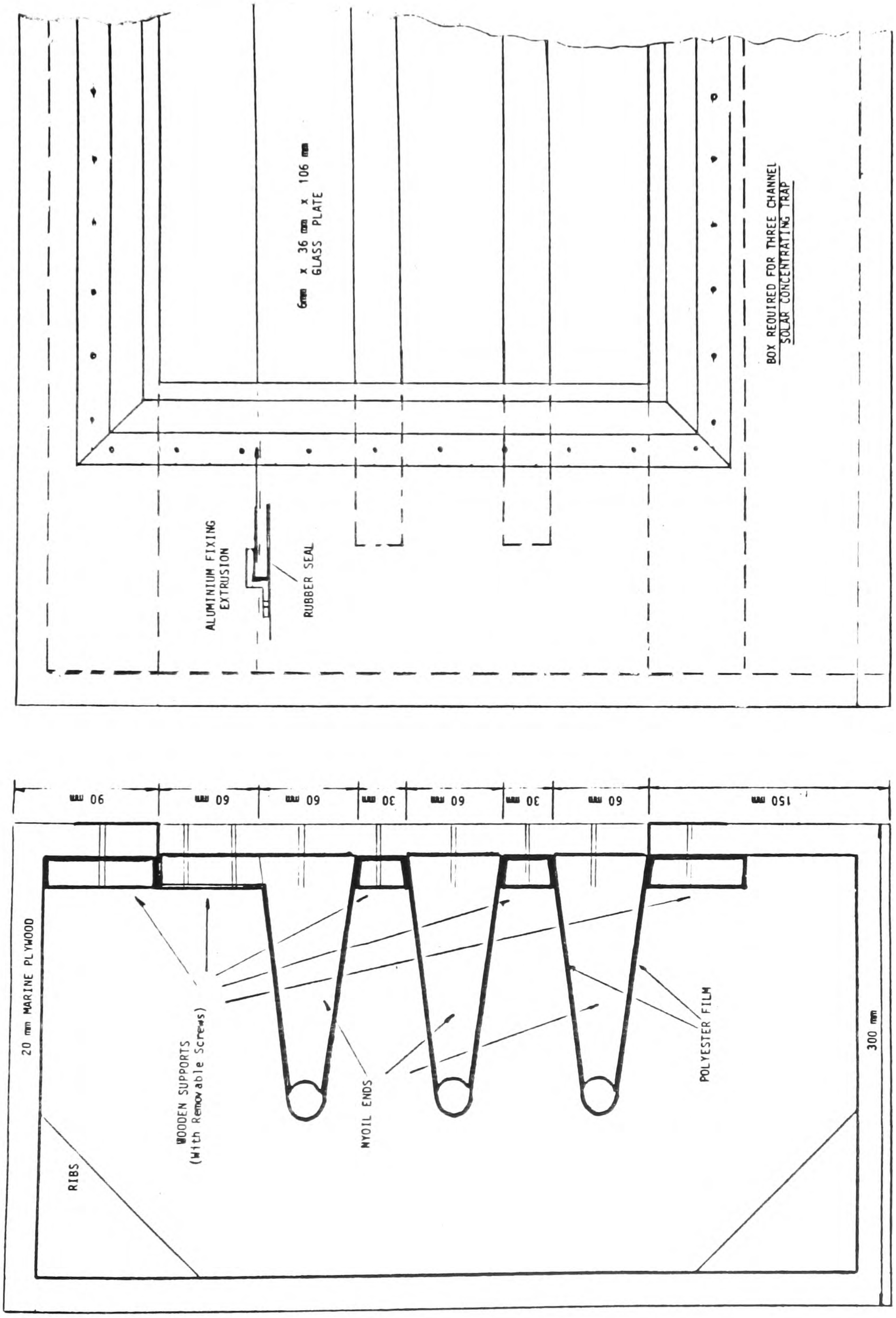

6mm x 36 mm x 106 mm
GLASS PLATE
BOX REQUIRED FOR THREE CHANNEL
SOLAR CONCENTRATING TRAP
ALUMINIUM FIXING
EXTRUSION
RUBBER SEAL
90 mm
60 mm
60 mm
30 mm
60 mm
30 mm
60 mm
150 mm
20 mm MARINE PLYWOOD
WOODEN SUPPORTS
(With Removable Screws)
NYOIL ENDS
POLYESTER FILM
300 mm
RIBS

Fig 4.1

SOLAR COLLECTOR END PLATES

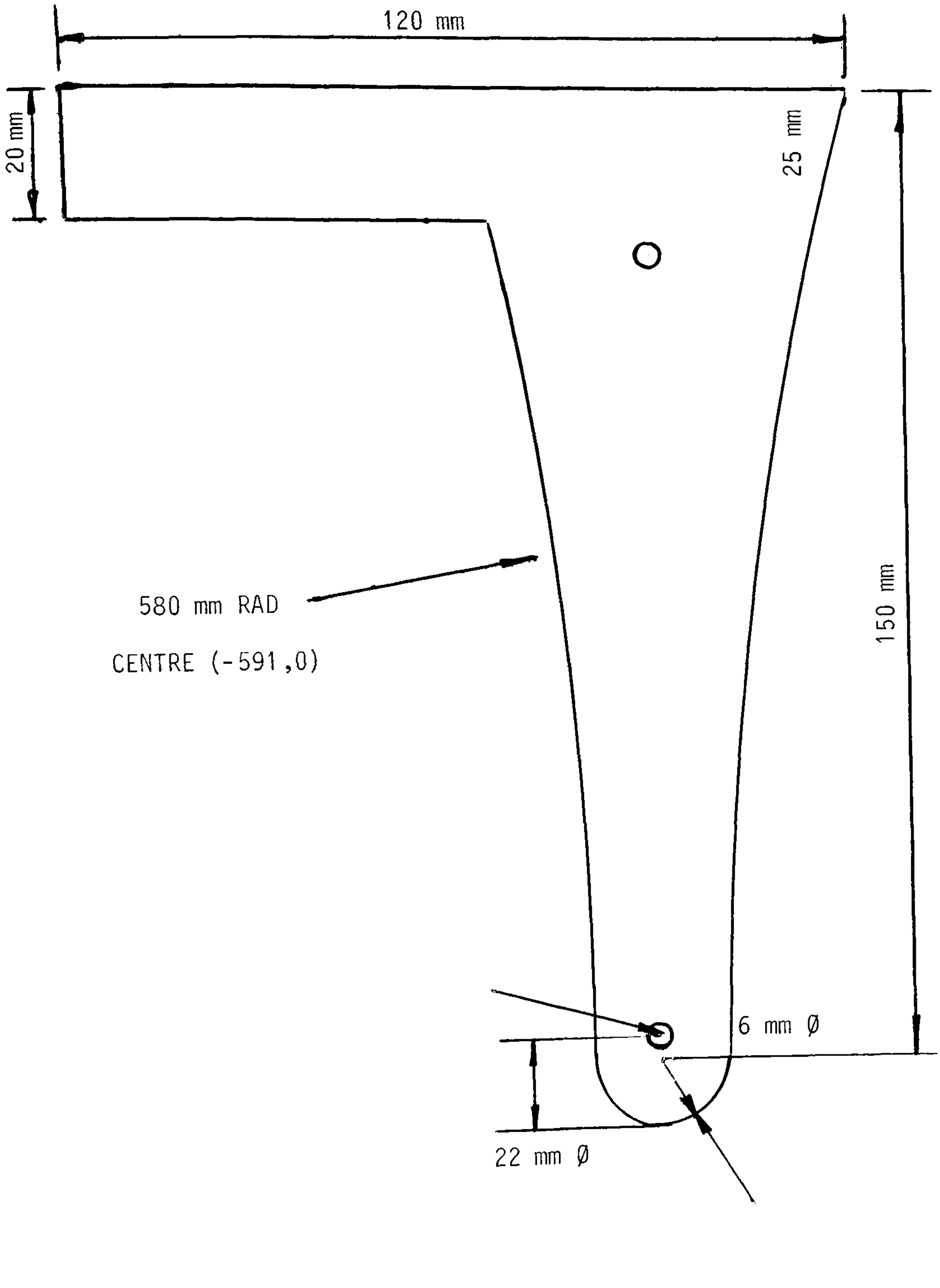


Fig 4.2

channels or just the central one which does not exhibit edge losses. It has been estimated that for a flow rate of 1ml per second a temperature rise of 20C across the collector should be possible.

4.2 THE PHYSICAL PROPERTIES OF THE COLLECTOR

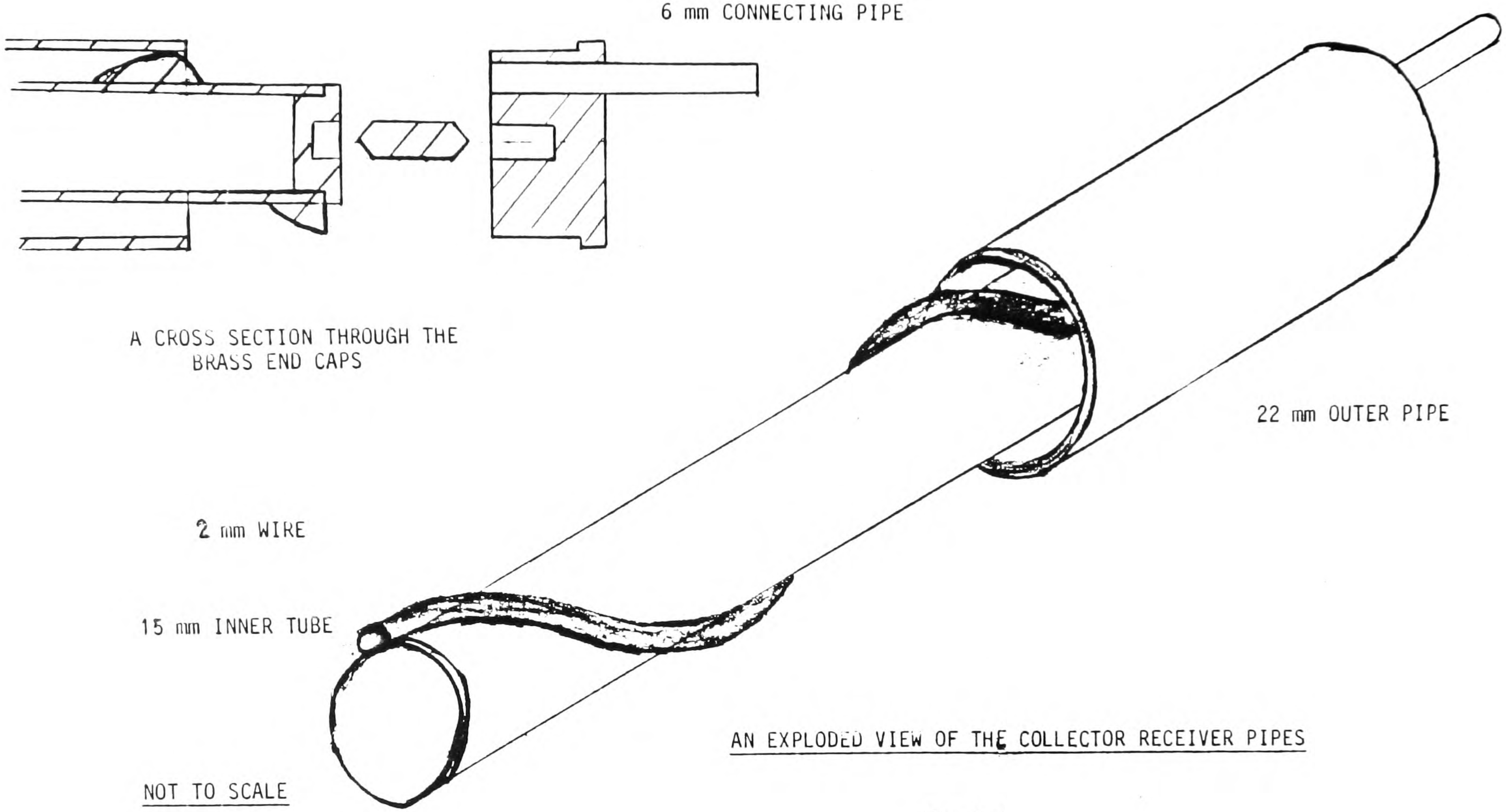
Once the choice of using metalised polyester film for the side reflecting surfaces had been made. The channel length was chosen to be 1m making the overall length of the collector 1.4m. It is advantageous to make them as long as possible (within reason) as this reduces the pipework and end losses but can make the collector cumbersome to handle.

The method of manufacturing the curved side surfaces had to take into account the end plates and the receiver. The end plates, as shown in Fig.4.1 and 4.2, were relatively easy to produce with their curvatures being machined on a CNC milling machine.

The receiver plate or pipe presented more of a choice, whether it should be micro-bore with a fin covering the 20mm width of the receiver or a large 22mm general purpose pipe. The 22mm pipe was prefered because the film could wrap around it with no joining necessary. For efficient operation the fluid temperature should be as close as possible to the receiver temperature. By using a 22mm diameter copper tube on its own where only the upper part of the tube receives radiation introduces two questions which need to be answered, namely what is the temperature difference around the section of the tube wall and what is it within the transfer fluid itself. A simple calculation shows that the temperature at the base of the pipe would be approx. 0.9C less than that at the top, which gives a large heat transfer area to the transfer fluid. However in a fully developed laminar flow which would undoubtedly be the case for flow rates of the order of $1mls^{-1}$, assumming an insolation level of $900Wm^{-2}$ and 55% efficiency, the temperature difference across the fluid, could be another 3.5C. This large temperature difference is not acceptable so a central tube as shown in Fig.4.3 was placed inside the receiver tube giving an estimated temperature differential of 0.7C across the fluid. This also reduced the thermal mass of the receiver by a factor of 4.5. A wire was coiled around the inner pipe to increase the path length of the fluid and to encourage turbulence. The connecting pipes which pass through the end plates were kept as close to the top of the receiver pipe as possible to discourage air locks in the receiver and to allow the use of fixing screws around the edge of the end plates. Using the same flow and insolation level as above for working out the temperature difference across the fluid it is estimated that approximately 30 Watts of power reaches the transfer fluid which would produce a temperature rise of 20C over the 3m of the collector.

The receiver should have as large an absorption coefficient as possible to illiminate any energy being reflected from the receiver surface, this was achieved by coating the copper pipe with a highly absorbing black paint which once baked onto the pipe becomes resistant to oils. The paint was applied using an air brush to produce a thin and even coating, allowed to dry naturally and then baked in an oven for three hours at 140C. The copper pipes were prepared using a hydrochloric acid (20%) etchant then washed in clean water and dried in hot air.

A former was required to hold the pipe work, film and end plates while the foam cured. Temperatures during the curing could reach 140C, therefore possible materials considered for the former were metals, plaster and wood. Metal formers were not possible to produce easily because of the length involved. Plaster of paris would have been expensive and required a mould, and one coat plaster produced shrinkage cracks under test. The choice was then narrowed to solid or hollow wooden formers. It was possible to manufacture either but hollow formers were produced because they were cheaper. The curved surface was made out of 4mm birch plywood glued onto a softwood base with 200mm spacers. The plywood was moulded into a hard wood top which was specially produced to fit onto the receiver pipe. Early testing showed



AN EXPLODED VIEW OF THE COLLECTOR RECEIVER PIPES

Fig 4.3

that the finish of the former needed to be highly polished to enable easy releasing. The completed formers are shown in Fig.4.4.

The Hyvis in the collector will be subjected to heating and cooling, which leads to the need of an expansion chamber. Calculations have shown that a volume of 288cm^3 per channel would be required for a temperature increase of 80C and that a cylindrical reservoir at one end of the collector would have to be approx. 8cm in diameter, would require connecting pipes to the main channel and have to be above the glass level of the collector. Due to the tilt of the collector this was discarded for a solution that does not require any pipework or extra manufacturing requirements. A system that gives a suitably sized reservoir over the top of the Hyvis with a large cross section for easy movement and very low internal pressure within the Hyvis. This reservoir, as shown in Fig.4.1 and 4.2, is 1m in length with a volume of $2.4 \times 10^{-3} m^3$ which is large enough for all three channels.

The receiver pipe is also subject to expansion from the same temperature changes, so to compensate for this the receiver stops short of the end plates by 1mm at each end. The micro bore tube through the nyloil ends is kept hyvis tight by the use of high temperature sealing rings held in position with brass caps.

It is necessary to insulate all the service pipework of the collector in order to reduce the heat loss to a minimum. The heat loss through the Hyvis is about 1 watt per unit length for a temperature gradient of 60C, it would therefore be appropriate to keep all other heat losses to the same order of magnitude. To achieve this requires a rigid foam with at least the same thickness as the depth of Hyvis, so insulation of 15cm was used on all receiver pipework which is the same insulation thickness as that used throughout chapter 3.

A PHOTOGRAPH OF THE HOLLOW WOODEN FORMERS PLACED IN POSITION IN THE COLLECTOR BOX

Fig. 4.4

4.3 THE PHYSICAL PROPERTIES OF THE MATERIALS

HYVIS

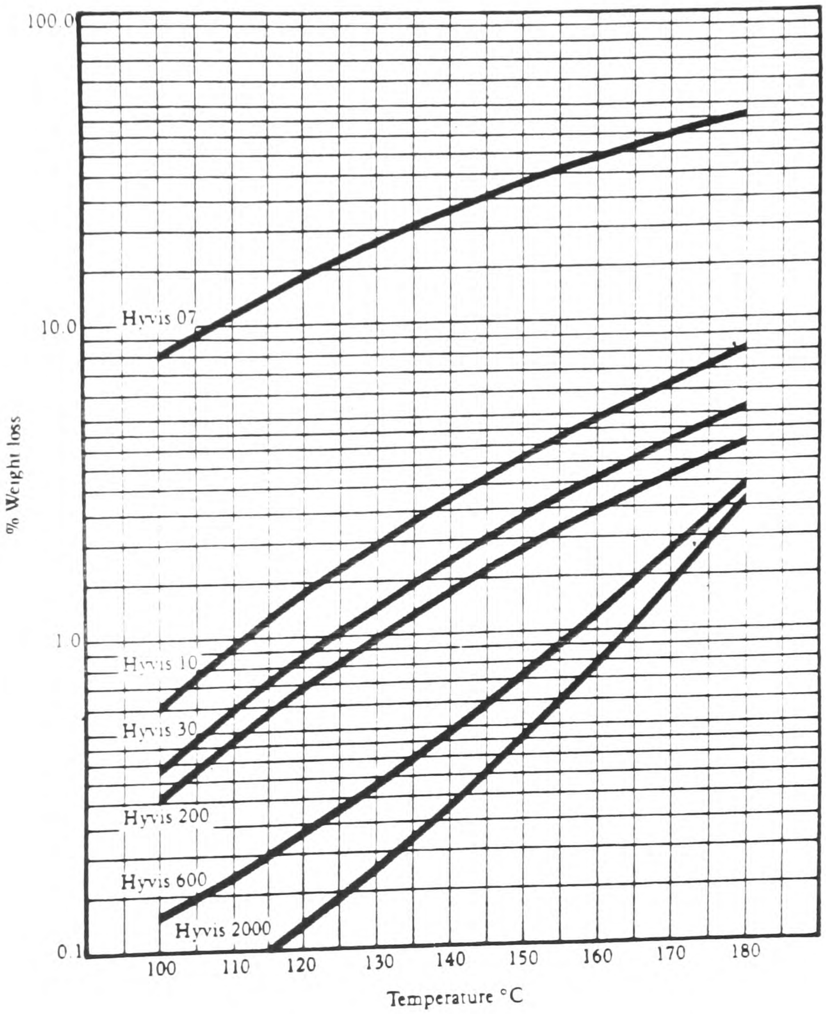
(Technical Information supplied by B.P. see ref.4.1.)

Hyvis polybutenes are polymers of C_4 hydrocarbons consisting essentially of isobutene. Within each grade of Hyvis a range of polymer molecular weights is present. Polybutenes differ from most other oils in decomposing by depolymerisation to give fragments which are considerably lower molecular weight than the average molecular weight of the grade itself. Depolymerisation does not proceed at a fast rate below temperatures of around 300C, losses measured at much lower temperatures are mainly due to true evaporation but depolymerisation has been detected at temperatures of 100C. Polybutenes which are stored hot for any length of time should be stored under an inert gas atmosphere in order to prevent the formation of explosive mixtures over the liquid. Evaporation rates at constant temperature and vapour pressure over a range of temperatures have been supplied by B.P. and are given in GRAPH.4.1 and GRAPH.4.2 respectfully. Polybutenes are chemically stable and not subject to atmospheric oxidation under ambient conditions. Their chemical stability is demonstrated by their retention of viscosity, tackiness and failure to harden, to become waxy, or to show any deterioration of colour on prolonged ageing at ambient temperatures.

PROPERTIES OF HYVIS:

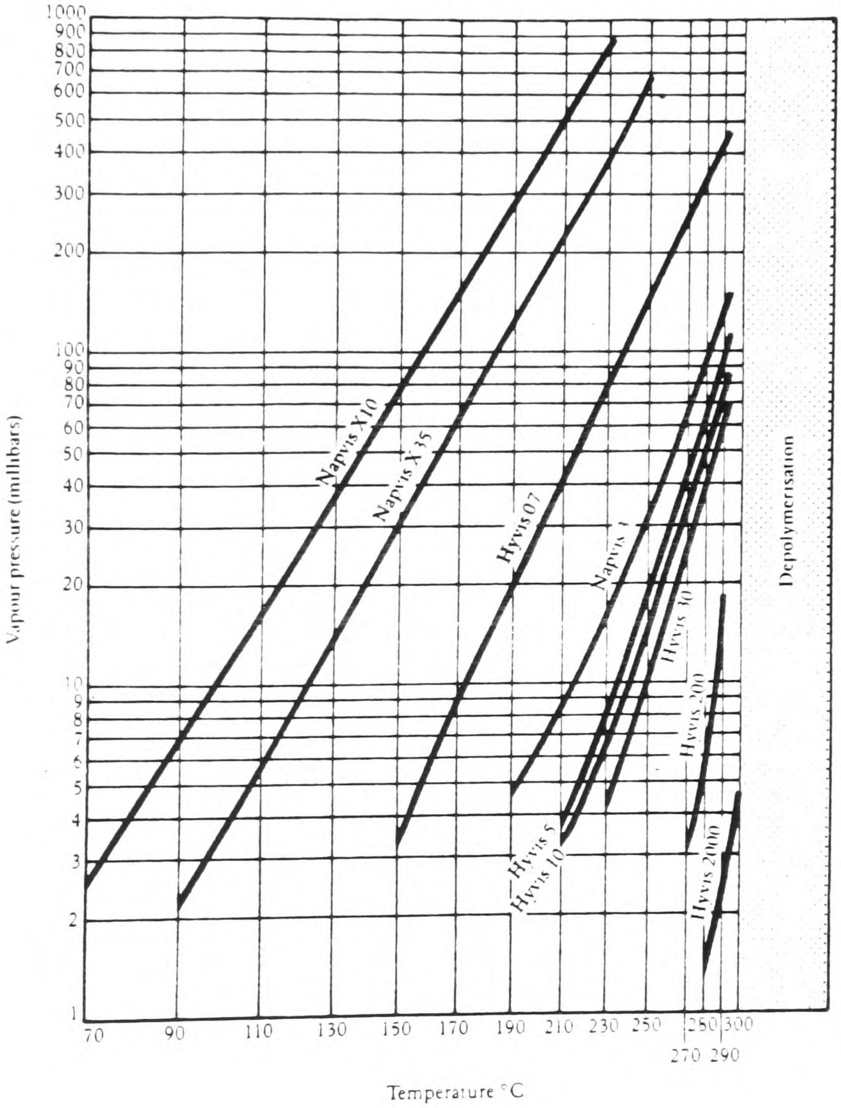
- Stable to light and air.
- Permanently non drying.
- Essentially water white and non staining.
- High Viscosity Indices.
- Compatible with a wide range of organic materials.
- Completely hydrophobic.
- Highly impermeable to gases and vapours.
- Negligible evapouration losses at ambient temperatures.
- Volatilise completely at elevated temperatures leaving no residues.
- Good electrical properties.

Evaporation loss on
Hyvis Polybutenes by
ASTM D972-56
(10 hour test period)



Graph 4.1

Vapour pressure vs. temperature of Hyvis and Napvis Polybutenes



Graph 4.2

Polybutenes are used in a range of applications including oil additives, adhesives, sealants, lubricants, electrical insulation plastics, rubber, bitumen and agriculture.

Typical physical properties are given in TABLE.4.1 and viscosity v temperature by GRAPH.4.3.

The measurement of solar transmittance which is not available has lead to the following experimentation in section 4.4.

POLYURETHANE FOAM (ISOFOAM RM606)
(For technical information see ref.4.2.)

This is a two component modified isocyanurate system producing Polyisocyanurate rigid (PIR) foam capable of withstanding temperatures up to 180C. Isofoam systems can be batched mixed using an electric drill giving at least 2000 rpm. Allow 30mins between batches to ensure first layer is hard. This PIR foam is an organic, combustible material and may present a fire risk in certain applications if exposed to fire and/or heat.

COMPONENT I (ISO):

This is a dark brown coloured low viscosity polymeric isocyanate composition based on undistilled diphenyl methane di-isocyanate (MDI). It is a highly reactive chemical, but of low vapour pressure. Avoid contact with skin and eyes.

COMPONENT R (RES):

This is a blend of polyols, R-11 blowing agent catalysts. Roll drum before use.

MIX RATIO:

RM606	ISO component :	60% by weight.
RM606	RES component :	40% by weight.

TYPICAL REACTION TIME & DENSITY (Both components at 20C.)

Cream time	12-18 secs.
Rise time	approx 105 secs.

Typical physical properties

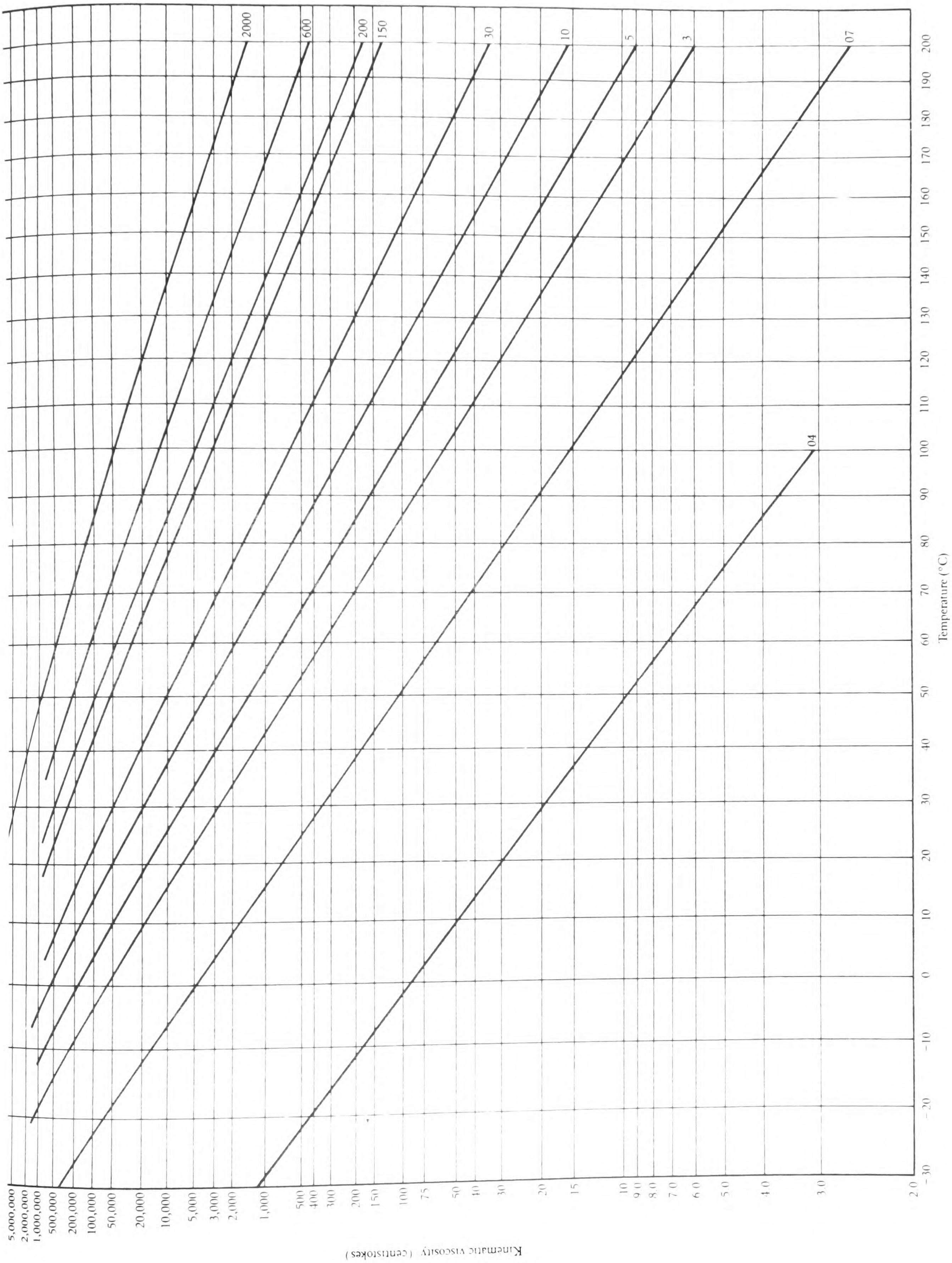
Hyvis Napvis		04 X35	07 07	— 3	5 —	10 10	30 30	150 —	200 200	600 —	2000 —
Viscosity at 100°C	(cSt)	3.3	13	57	103	225	635	3065	4250	12200	40500
	(SSU)	37	70	270	480	1050	2960	14300	20000	57000	190000
Flash point PMCC	(°C)	120	130	140	155	165	170	175	175	180	190
Flash point COC	(°C)	135	145	155	190	210	240	250	270	275	280
Pour point	(°C)	<−60	−30	−21	−12	−7	4	18	24	35	50
Relative density at 15.5°C	(g/cm^3)	0.830	0.851	0.869	0.884	0.894	0.902	0.911	0.914	0.918	0.921
Colour	(Hazen)	50	50	50	50	50	50	50	50	50	50
Viscosity index		—	—	—	100	128	181	246	264	306	378
Refractive index		1.460	1.474	1.487	1.490	1.494	1.498	1.503	1.504	1.505	1.508
Bromine number	(gBr_2/100g)	52	40	27	20	16	12	8	6	4	3
Acid no.	(mgKOH/g)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Water content	(ppm)	40	40	40	40	40	40	40	40	40	40
Sulphur	(ppm)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Iron	(ppm)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Inorganic chlorine	(ppm)	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Organic chlorine	(ppm)	50	50	50	50	50	50	50	50	50	50

Note:
For viscosities above 100 cSt, viscosity (in SSU) = viscosity (in cSt) × 4.664 (at 100°C).
For viscosities below 100 cSt, conversion tables should be used.

Hyvis 2000

	Temperature	Conductivity
Thermal Conductivity	18	0.18 $Wm^{-1}\,^oC^{-1}$
	42	0.16 $Wm^{-1}\,^oC^{-1}$
	62	0.14 $Wm^{-1}\,^oC^{-1}$
Thermal Expansion	-	$6 \times 10^{-4}\,^oC^{-1}$
Thermal Capacitance	38	2000 $J\ Kg^{-1}\,^oC^{-1}$

Table 4.1



viscosity v temperature

Graph 4.3

Tack free time	approx 110 secs.
Time between layers	30 mins.
Moulded, overall density	64 kgm^{-3}.

THERMAL CONDUCTIVITY $Wm^{-1}k^{-1}$:

Initial	0.017
aged 14 days @ 180C	0.022
aged 140 days @ 180C	0.026

NYLOIL

(For technical information see ref. 4.3).

Nyloil has free machining properties, is resistant to creep and can is supplied in sheet form.

Thermal expansion	10^{-4}
Thermal conductivity	$0.5Wm^{-1}C^{-1}$

RELEASE AGENT CR180

(For technical information see ref.4.4)

This is a high temperature resistant paste release agent which in addition to conventional release of low desity insulation is also used for mould sealing/conditioning and therefore suitable for sealing off the wooden formers. The wax has proven itself resistant up to temperatures of 150C. Three coats were applied with a cloth and polished.

COMPONENTS:

Active.

Aliphatic solv.

RELEASE AGENT SUPER S AEROSOL

(For technical information see ref.4.4)

This is a very versatile system for many types of solid polurathene, polyesters and epoxies.

COMPONENTS:

Active.

Fluorinated solv.

GLASS PLATE

(For technical information see ref.4.5)

Glass is toughtened by subjecting it to a heating and cooling process whereby high compressive stresses are set up at the surfaces with balancing tensile stresses in the centre. These balencing stresses gives the glass its increased strenght. It will only break under extreme loads by bending or by severe impact with a sharp object. Toughtened glass is up to five times stronger than ordinary glass and if broken disintegrates into small relatively harmless pieces which are neither large enough or sharp enough to cause serious injury. The glass is also capable of withstanding extremes of heat and cold. At 250C it can be sprayed with ice water.

Thermal conductivity	1.4 $Wm^{-1}C^{-1}$.
Thermal capacitance	0.75 $KJkg^{-1}C^{-1}$.

VACUUM METALLISED-POLYESTER SURFACE

(For technical information see ref.4.6)

Very low permeability to oxygen and moisture vapour. High reflectivity to light with decorative appearance.

Polyester can withstand temperatures up to 160C but a tarnishing effect is noticable with prolonged heating at 150C.

SPECIFICATION:

Maximum reel width	1200mm
Thickness 400 gauge	(100um)
Density.	$1.03x10^{-3}$ kgm^{-3}
thermal expansion.	$25x10^{-6}C^{-1}$
thermal conductivity.	0.17 $Wm^{-1}C^{-1}$

HERMETITE POT BLACK

(For technical information see ref.4.7)

This is a heat curing satin black paint that withstands up to 450C. It is not prone to cracking or flaking. Surfaces to be painted must be clean, dry, free from rust, dirt, grease and loose or flaking paint.

APPLICATION:

Stir the paint thoroughly and apply thinly with a soft paint brush preferably to bare metal. Allow to dry naturally for 12 hours. Full cure is acheived when subjected to heat in service. Once cured, Pot Black is resistant to petrol, oils and anti-freeze. Pot Black is an xylene based paint and can be harmful until dry.

PTFE (Polytetrafluoroethylene)

PTFE resins are high molecular weight polymers and do not melt as do most thermoplastics. PTFE is tough and ductile, offering excellent properties from -450^{o}F to 500^{o}F.

Thermal expansion 73-140^{o}F	$10 \times 10^{-5} C^{-1}$.
Thermal conductivity	0.35 $Wm^{-1}C^{-1}$.

Non-flammable.

RESISTANT TO:

Mineral acids, alkalis, solvents (alcohols, ketones, aromatic, hydrocarbons, chlorinated hydrocarbons), detergents, Greases and oils.

SILICON RUBBER

(For technical information see ref.4.8)

A translucent, one component, room temperature curing silicone elastomer. Cross linking takes place in the presence of moisture in the air to form a flexible resilient silicone rubber. During cure the material liberates acetic acid.

USES:

Will bond to most clean surfaces.

TECHNICAL SPECIFICATION:

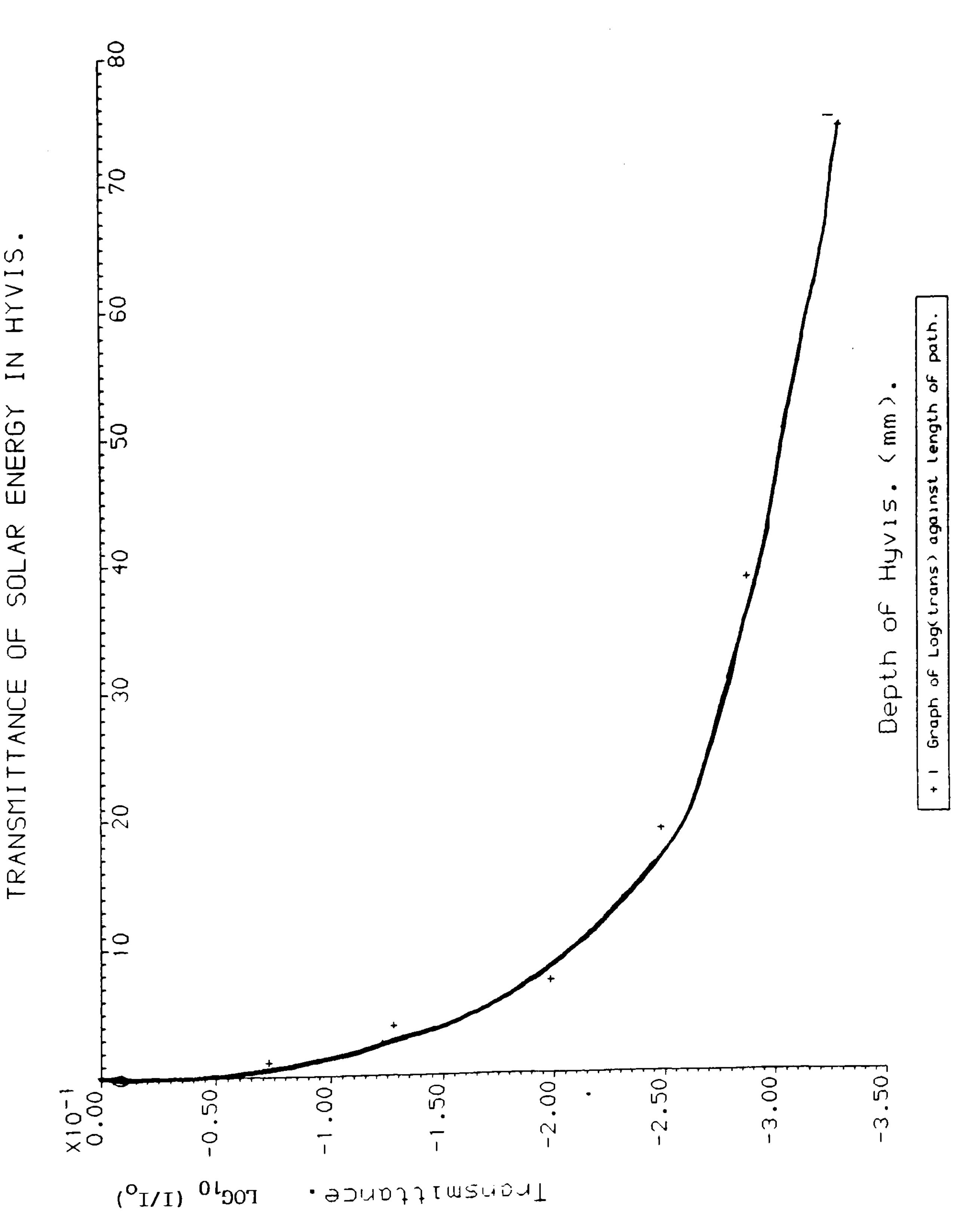
Cure time	24hr for 3mm bead.
Temp. range	-50C to 250C.
Tensile strenght	1.7MPa.
Elongation	400%.

4.4 THE EXPERIMENTAL MEASUREMENT OF SOLAR TRANSMITTANCE THROUGH HYVIS

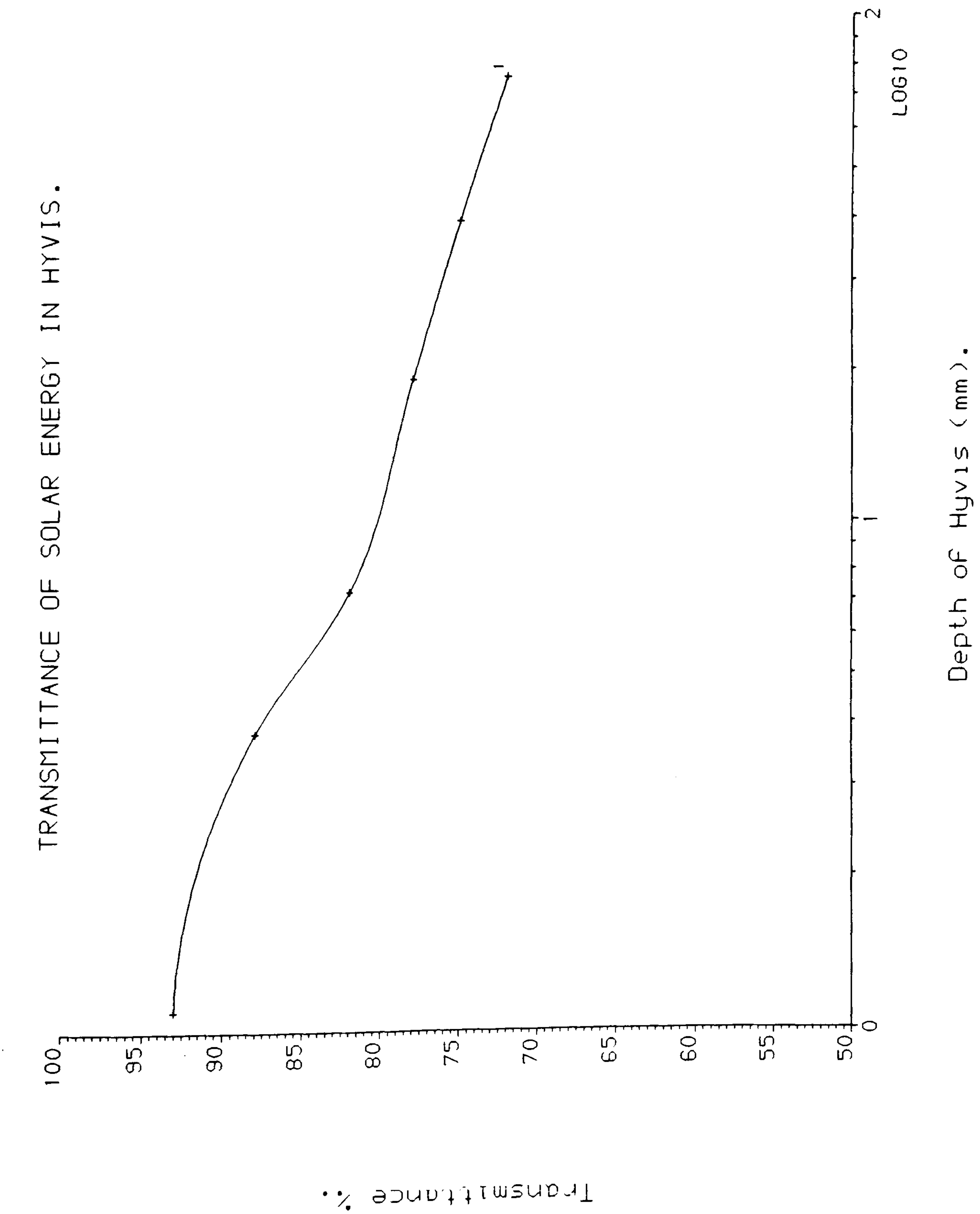
The transmittance of solar radiation through Hyvis is required to predict the amount of energy absorbed in the Hyvis and conseqently the amount of energy reaching the collector.

S.Brown (1980) reports on the transmittance of Hyvis to solar radiation. His results are presented in the $\log(I/I_0)$ versus depth graph given in GRAPH 4.4. The transmittance versus depth of Hyvis of GRAPH 4.5 has been approximated to a straight line, and it is this relationship that has been used throughout the simuation. Unfortuneately S.Brown's results were confined to a maximum path length of 75mm, hence longer paths had to be extrapolated.

Following a comparison between collector theoretical and experimental performance it became evident that the transmission within Hyvis is considerably lower than that reported by Brown especially for longer paths, consequently it was decided to repeat the transmission experiments. This was carried out using number of different depth Hyvis cells of 2, 10, 20 and 30cms in depth and approximately 100cm^2 in cross section. The cross section needed to be substantially greater than the beam of light used, so as to avoid reflections from the cell walls. The first experiment consisted of a high temperature light source (24V Quartz Hallogen bulb with an emitting temperature of approximately 3400C). This was required to try and emulate the radiation distribution of the sun. The apparatus consisted of a


TRANSMITTANCE OF SOLAR ENERGY IN HYVIS.
Transmittance. LOG_{10} (I/I_o)
X10^{-1}
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
10
20
30
40
50
60
70
80
Depth of Hyvis. (mm).
+ I Graph of Log(trans) against length of path.

Graph 4.4

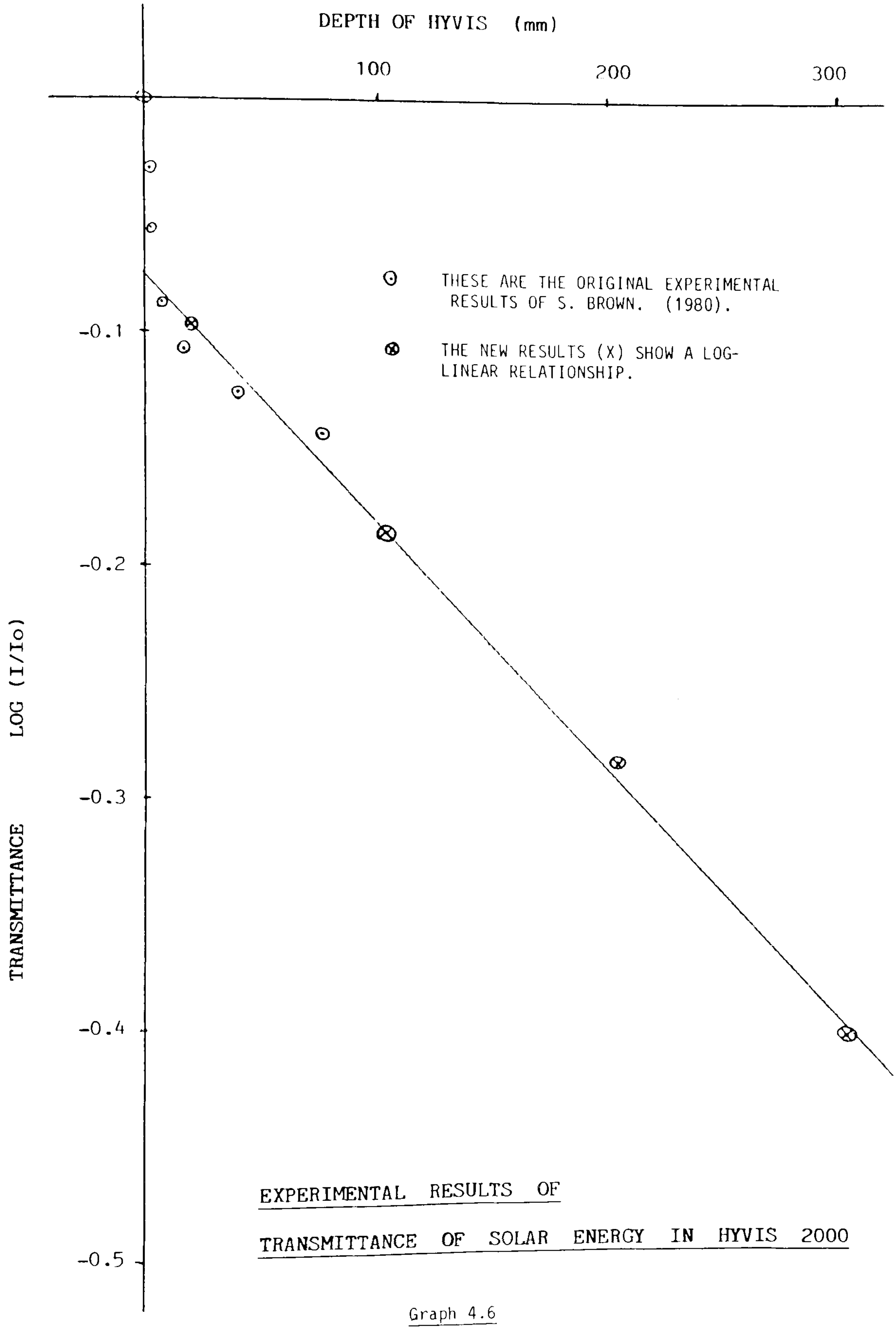

TRANSMITTANCE OF SOLAR ENERGY IN HYVIS.
Transmittance %.
Depth of Hyvis (mm).
LOG10
100
95
90
85
80
75
70
65
60
55
50
0
1
2

Graph 4.5

24V voltage stabilizied light source and lens system arranged so as to produce parallel light through the cell and onto a solarimeter detector. This proved to be the better of the systems tried but inconsistency in the results eventually lead to abandoning this method. It was believed that the apparent focussing of the Hyvis in the larger cells caused a slight change in the image of the bulb filliment on the detector and was the major influence of the inconsistency. This could be demonstrated by slightly moving the detector with no cell present.

It therefore seemed appropriate to use the sun itself for the measurements. The apparatus consisted of a vertical system as before but with a swivelled mirror to reflect the sun beam vertically through the Hyvis cell. Using the perfectly parallel beam of the sun through the cell gave reasonably consistent results. Any slight variation in insolation was minimised by averaging the results over a 30 second interval for both with and without cell readings. The experiment was conducted on a clear day when intensity levels are consistent. GRAPH 4.6 shows the results from this experiment. It can be seen from this graph that if the shallow depths are ignored that Beer's law holds true and the log-linear relationship could be used for the simulation in future.

Compared with the results of S.Brown it can be seen from GRAPH 4.7 that there is good similarity for the 2cm cell but for the larger cells the transmittance is not as favourable as previously predicted. It seems evident from these results that the predicted computer simulation which was based on the original results is approximately 20% better than is now thought possible. This will be apparent when the simulated results are compared with the experimental results in chapter 6.

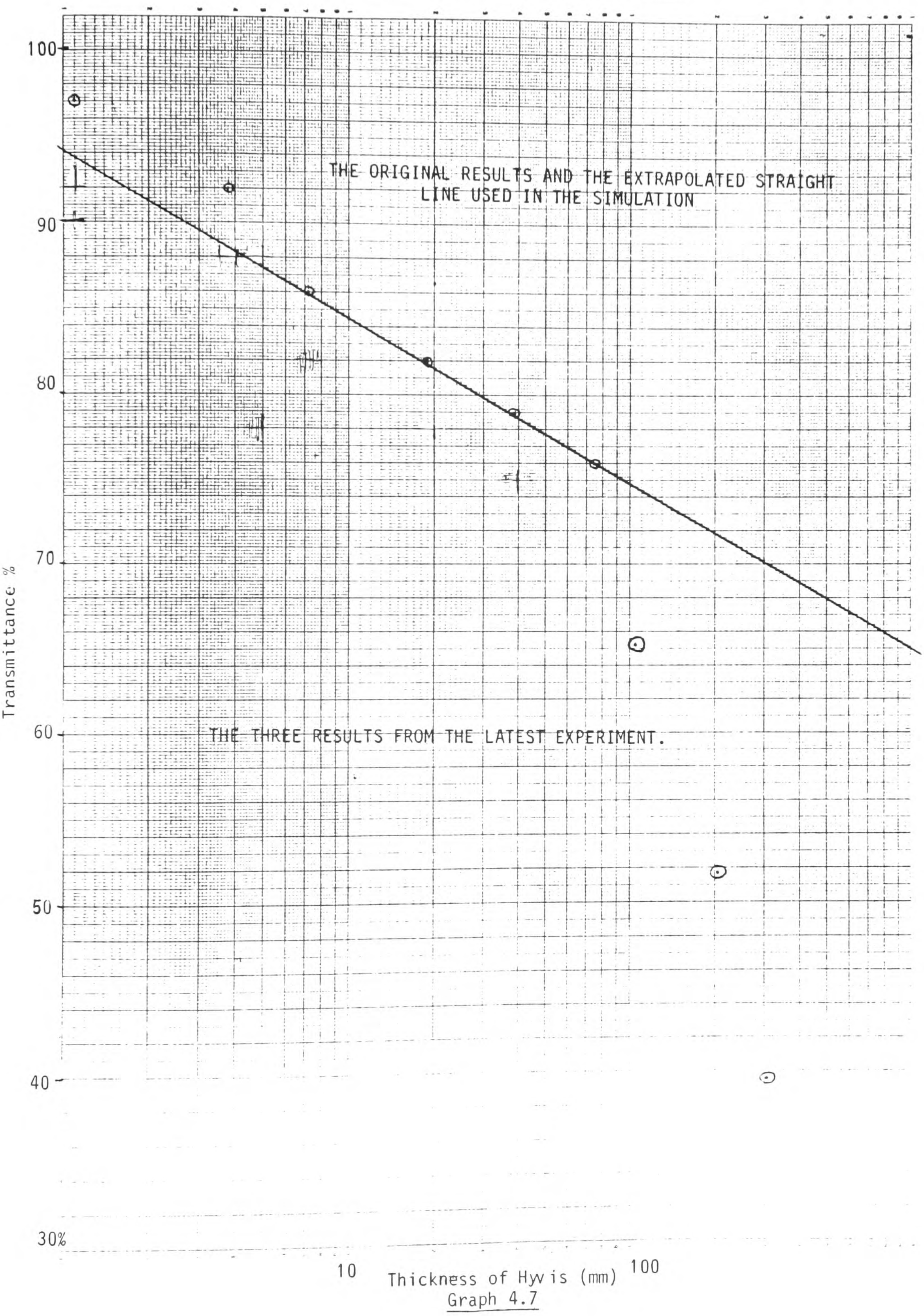


EXPERIMENTAL RESULTS OF

TRANSMITTANCE OF SOLAR ENERGY IN HYVIS 2000

Graph 4.6

TRANSMITTANCE OF SOLAR ENERGY IN HYVIS



Graph 4.7

4.5 THE PRACTICAL CONSTRUCTION OF THE COLLECTOR

The fist step in the construction was the production of six wooden formers each identical and 1 metre in length as shown previously in Fig.4.4. They were then coated with the special high temperature wax residue CR 180C to aid their easy release.

The collector box was then made from 20mm marine plywood, its overall measurements being 1.4x0.8x0.3 m^{-3}, the lid in the top being used to secure the three formers and the wooden mold of the reservoir. The lid was then replaced and secured to the box.

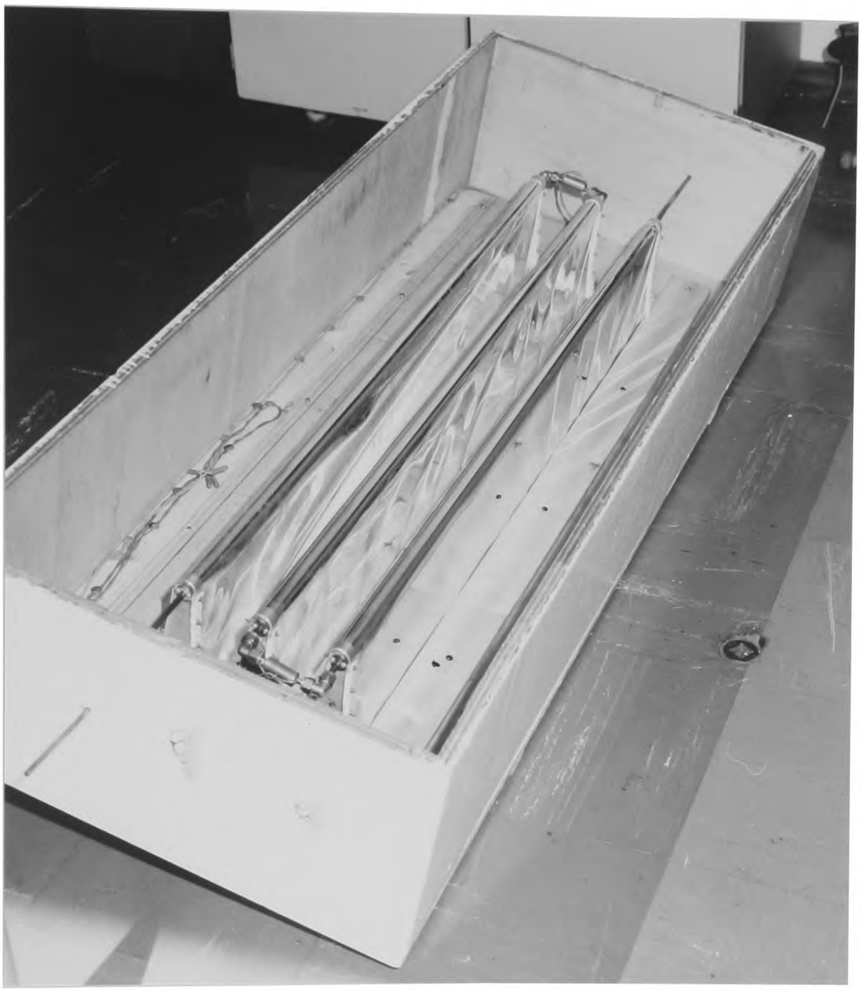
Before the construction of the collector could continue the receiver pipes had to be assembled and painted. (see section 4.2).

Once these were ready the bottom of the box was removed and the blackened receiver pipes were laid on the formers and the nyloil ends of the collector screwed to the top of the box in position. The 'O' ring seals of the receiver pipe were then fixed in place with a brass plate screwed to the nyloil as shown in Fig.4.5.

The Four (type K) thermocouples to record the temperature gradient of the Hyvis were fixed to the central nyloil end at 2.0,4.0,8.0 and 12.0 cm normal to the receiver, by placing the thermocouple wire through a small countersunk hole which was sealed with araldite.

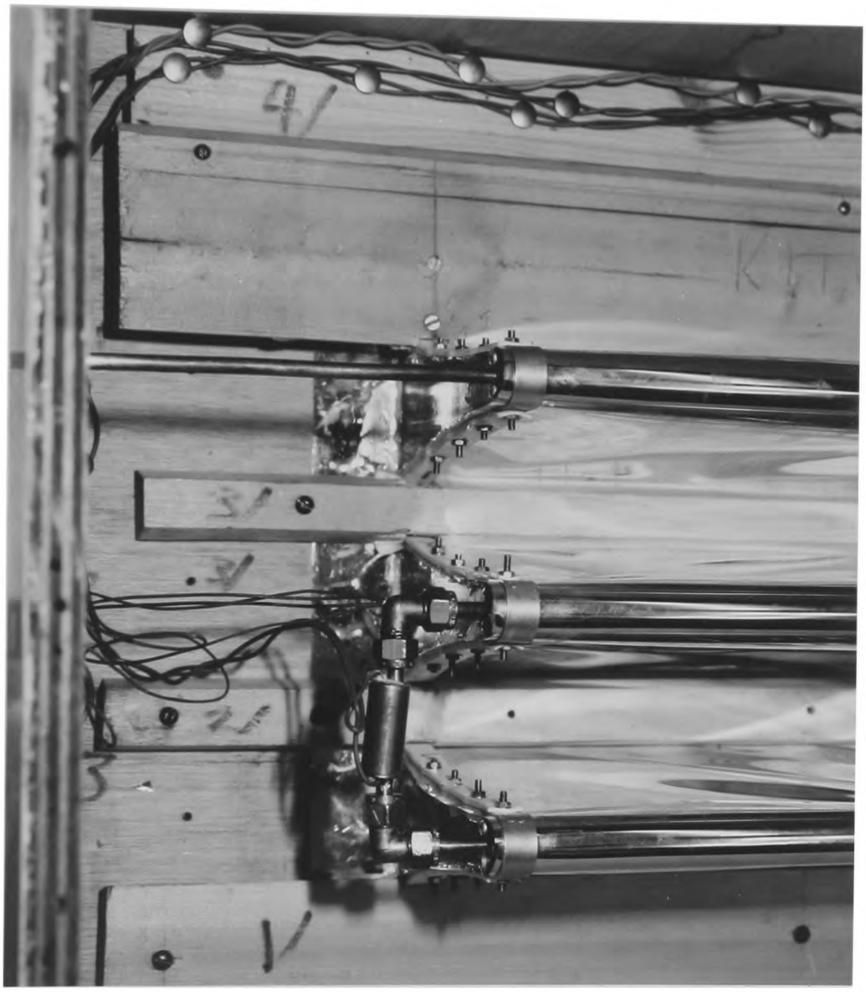
The receiver pipes were joined to make one continuous conduit, see Fig.4.6. At these joins platinium resistance thermometers were attached to the pipe so as to accurately record the water temperatures at either end of the central channel. The system was then tested with water to check for leaks.

The polyester film was then laid over the formers and fastened on either side and between each channel with wooden battens these kept the film tight over the formers Fig.4.6. The film was



A PHOTOGRAPH SHOWING THE RECEIVER PIPES AND POLYESTER FILM DURING THE CONSTRUCTION OF THE COLLECTOR

Fig. 4.5



A PHOTOGRAPH SHOWING A PLATINUM RESISTANCE THERMOMETER ATTACHED TO THE RECEIVER PIPE OF THE COLLECTOR

Fig. 4.6

then sealed to the nyloil ends using silicon rubber and strips of PTFE and aluminium bolted horizontally through the nyloil. Once the film was secure, the formers were removed, sprayed with the mold release 'Super Release S' and replaced. The whole system was then tested once again for leaks.

The collector was then ready for the insulation foam. This required mechanically mixing the two components using a high speed drill fitted with an agitator and quickly pooring the batch into the box as evenly as possible within the 20 secs available before frothing. Experience with preliminary testing had indicated that the foam would adhere to the film better if it was damp and would be best cured in layers, however this was not successful, was difficult to control and created air pockets within the foam. Once complete the surplus foam was cut off and the lid replaced.

The formers were removed and the process of filling the collector with Hyvis started. To reduce its viscosity the Hyvis was preheated in its drum to 80C using heating bandages. To increase the flow rate the outlet pipe was wrapped in a heating bandage and the drum pressurised to force the Hyvis through the pipe. After 30 hours the filling was complete, it only remained to seal the glass top with silicon rubber and fix in position with aluminium strips. The collector was then placed upright and to inhibit condensation within the reservoir a breather tube of silica gel (self indicating) was fitted as shown in Fig.4.7. The collector was left for the Hyvis to settle its construction being complete.

A PHOTOGRAPH SHOWING THE COMPLETED COLLECTOR

Fig. 4.7

REFERENCES

4.1. BP Chemicals Limited. BP Technical note: BP 104.

4.2. Baxenden Chemicals Limited. RM606.

4.3. Granby Plastics Ltd. Leicester. LE4 7JD.

4.4. Marbo Italia. S.p.A.

4.5. Walterton Toughened Glass Ltd. Llantrisant.

4.6. Convertec International Ltd.

4.7. Hermetite Products Ltd.

4.8. RS Components Ltd.

CHAPTER 5

EXPERIMENTAL PROCEEDURE

5.1 INTRODUCTION

Once the collector had been commissioned it was possible to begin the transient testing of the collector for typical weather conditions. From the experimentation it should be possible to produce a graph of efficiency (n) against differential temperature, the temperature difference between mean receiver and ambient temperatures, per unit incident energy (DT/E), so that the practical and theoretical results can be compared. It should also be possible to determine the time constant of the collector from the experimental results although this will require special operating conditions. The ultimate objective, however is the ability to accurately predict system performance for all climatic conditions.

A currently available test system based on the transient collector test method {ref.5.1} was used to perform the experiment. This system, outlined in section 5.2 is capable of recording all the temperatures and insolation levels required for the operating analysis of the collector. All measurements were taken using a microcomputer-controlled acquisition system which stored data on flexible disks at one minute intervals for final data reduction and analysis. It can be seen from the test equipment that care has been taken to minimise experimental error especially for the transfer fluid flow rate and temperature readings. Insolation levels were recorded with the use of an epply pyranometer placed on the collector surface to ensure readings for the plane of the collector. From the recorded data the efficiency and energy gained by the collector has been evaluated and presented in graphical form.

The angle between the collector's optic axis and the transverse or radial component of the solar beam, the radial angle, can be minimized by tilting the collector and by taking results when the sun is axially overhead. For the testing it was convenient to place the collector on a low roof that faces the south east and inclined at an angle of 35^{o} to the horizontal. This inclination as can be seen from the graphs in section 5.4 minimises the radial angle throughout the recording period. Results taken when either the radial or axial angles are large should be ignored since the optical efficiency of the collector falls off for either angle above 20^{o} {ref.5.2}. (Both these angles are defined by the solar trajectory and are explained in section 5.5.2.)

The majority of the experiments results were taken between 7:00am and 12:00 noon solar time because of the south easterly direction of the collector. From the data several graphs of the instantaneous parameters have been plotted and are shown in section 5.5.5. These graphs have then been used to estimate the collector's steady state performance from which the required efficiency graph has been constructed.

5.2 AN OUTLINE OF THE EXPERIMENTAL PROCEDURE

5.2.1 INTRODUCTION

The aim of the experiment is to obtain the collector's efficiency at steady state conditions for various operating conditions. However with so many parameters it is more realistic to obtain the efficiency under transient conditions from which the steady state values can be derived. Such a method requires a continuous evaluation of collector power and insolation level. The method used to determine the rate of energy gained by the transfer fluid uses a comparison with a water heater to evaluate the power output from the collector. The efficiency as predicted in chapters 2 & 3 varies with the differential temperature of the collector, and so it is also important that the apparatus can accurately control both a constant transfer fluid flow as well as maintaining a uniform input temperature in order to keep the temperature differential of the collector as steady as possible. The equipment or interface shown in fig.5.1 is currently available at the Polytechnic of Wales for testing the thermal performance of solar collectors in variable conditions. Water at a constant temperature is pumped through an electrical heater before it enters the collector. Once its passed through the collector the water cools as it returns to the constant temperature bath. From the temperatures of the water as it passes around the system the transient efficiency of the collector can be evaluated and is discussed fully in section 5.2.2. From the information recorded by this instrumentation it was possible to plot the graphs of insolation, efficiency, differential temperature per unit insolation, energy gain, initial water temperature and average receiver temperature. The analysis of these graphs form the basis of all the collector performance predictions and is therefore fundumental to the conclusions that follows in chapter 6.

5.2.2. THE TEST SYSTEM FOR THE SOLAR COLLECTORS

The collector efficiency is given by:-

$$n = \frac{\text{output power}}{\text{incident irradiance x collector area}} = \frac{Q}{EA}$$

Q is the rate of energy gain, E is the insolation determined by the solarimeter or pyranometer and A is the collector surface area. Then from Fig.5.1 Q is given by:-

$$Q = C \frac{dm}{dt} (T_3 - T_2)$$

where C is the fluid heat capacity and dm/dt is the mass flow rate.

During the building of the collector the number of channels were reduced to three to minimise fabrication time, consequently the effective area of the collector was only 0.18 m^2. To obtain the required temperature rise in the transfer fluid the flow

BLOCK DIAGRAM OF TEST SYSTEM FOR SOLAR COLLECTOR

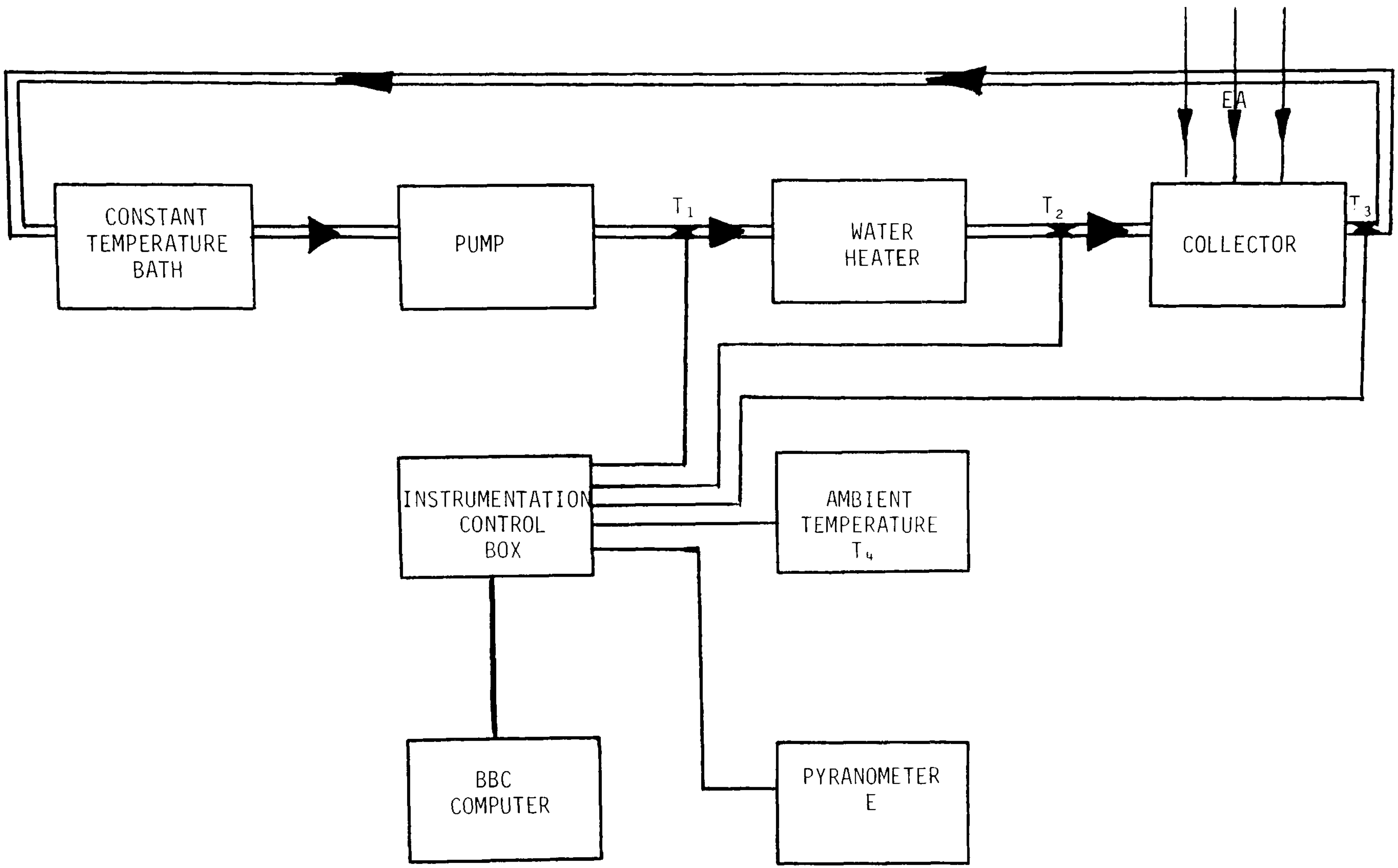


Fig 5.1

rate needed to be set at approximately $1 mls^{-1}$ which is dangerously close to the lower limit of the peristatic pump. This assumes $T_3-T_2 \simeq 10^{o}C$, for an output power 30W.

Measuring such low rates of flow to within 1% other than by manual methods presents obvious difficulties so a comparison method was used where an electrical heater is used to increase the temperature of the inlet fluid. If P is the electrical heater power then

$$\frac{dm}{dt} = \frac{P}{C(T_2 - T_1)}$$

and since C is approximately independent of temperature

$$Q = \frac{P(T_3 - T_2)}{(T_2 - T_1)}$$

and the efficiency becomes:-

$$n = \frac{P(T_3 - T_2)}{(T_2 - T_1)EA}$$

The differential temperature per unit insolation is evaluated from the equation:-

$$\frac{DT}{E} = \{ \frac{T_2 + T_3}{2} - T_4\}/E$$

5.3 THE EXPERIMENTAL MEASUREMENTS

The accuracy of the experiments depends primarily on the measurements of temperature differences, P and E. In order that the overall accuracy of n and DT/E is less than 5% the instrumentation should be designed so that P, E, T_2-T_1, T_3-T_2, T_2, T_3 and T_4 can be determined to within 1%.

TEMPERATURES:

The temperature of the receiver plate is kept constant throughout the experiment by the use of a thermastatically controlled water bath while the temperature rise of the transfer fluid is kept to approximately $10^{o}C$ by adjustment of the flow rate. This adjustment is necessary because the instrumentation is only designed to record temperature differences of up to $15^{o}C$, while values less than $10^{o}C$ would reduce the accuracy of the temperature measurement. Similarly T_2-T_1 should be kept to approximately the same value to reduce experimental errors. The two temperature differences were determined using platinum resistance thermometers in a bridge arrangement as shown in Fig.5.2. The output from the bridge being processed by amplifiers and switches to give the required input voltages to the computer for recording.

HEATER POWER:

The power P can be determined from values of Voltage Vp and current Ip of the supply into the electrical heater, as shown in Fig.5.2. These parameters are sensed and converted into DC voltages by means of the fixed resistors and the two AC/DC converters.

ANALOGUE SWITCHES AND COMPUTER INTERFACE:

The BBC computer has one parallel input/output port but can handle four input channels through its analogue input port which it can sample at 10 ms intervals. So far eight parameters have been mentioned which need to be recorded. These are (T_2-T_1), (T_3-T_2), T_2, T_4, the bridge supply voltage (15Vmax), E, Vp and Ip. With so many inputs it is necessary to incorporate analog switches to change from one input parameter to another. The design of these switches is such that (T_2-T_1) and (T_3-T_2) are sequentially directed by analogue switch (a) to one analog input, while T_2 and T_4 are sequentially directed to analog switch (b) in the same way. A third analog multiplexer switch (c) is used to sequentially sample E, V_0, Vp and Ip.These switches are all controlled by the parallel input/output port and are shown in the outline diagram of

THE FUNCTIONAL PARTS OF THE SOLAR COLLECTOR TEST SYSTEM

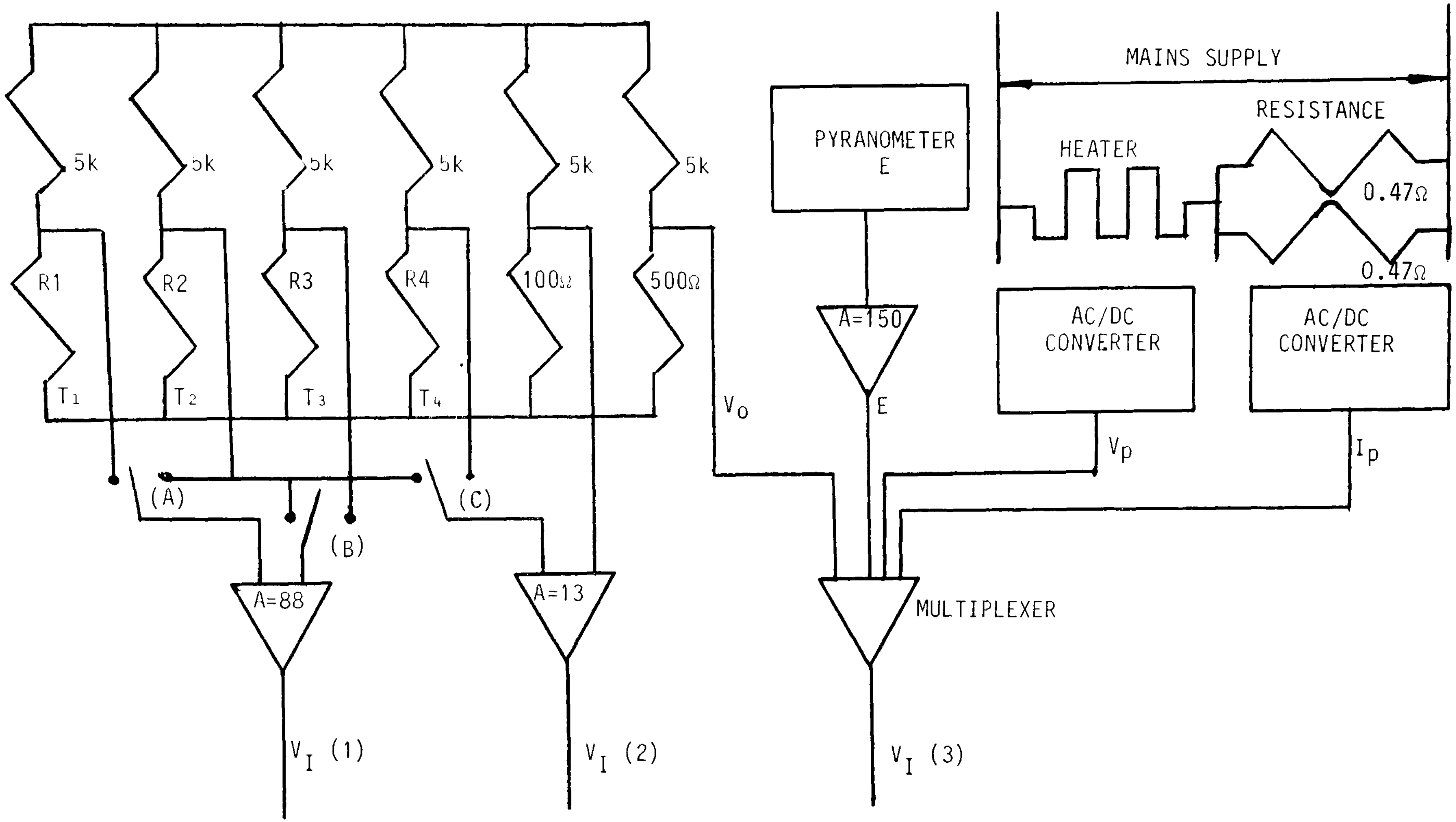


Fig 5.2

Fig.5.2. The complete sampling cycle, discussed in section 5.4.2, being repeated every 5 secs.

5.4 THE EXPERIMENTAL RECORDING

5.4.1. INTRODUCTION

Once the collector and recording apparatus was operational the experimental recording could be undertaken. The experiment was repeated for different input fluid temperatures (20^o-80^o) so proir to each run the water reservoir bath was preheated to the correct temperature. The results were then recorded and filed on disc using a BBC computer. The recorded data consisted of the starting time, the time relative to the start, the differences in temperature T_2-T_1 and T_3-T_2, the actual temperatures T_2 and T_4, the insolation and the power of the heater. These results were then analysed and plotted on three different graphs. The first graph plots the incident angle that the solar beam makes with the normal to the collector (optic axis) in the axial (Ix) and radial (Iy) directions as shown in Fig.5.4. The second graph shows how the efficiency and DT/E alter with insolation while the third graph shows the variation in input temperature, collector average temperature, and how the energy gained by the collectór changes with the insolation, throughout the experimental run. The steady state graph of efficiency against DT/E was then constructed from data taken from these graphs. This was difficult to assess as the collector never reached a truely steady state which could only be summized from information gained from the graphs of the transient conditions.

5.4.2. THE PROGRAM THAT RECORDS THE DATA (SOL)

The experimental data as defined in section 5.3 can be sampled periodically by the BBC analog port in conjunction with the parallel input/output port. The objective of recording the data was therfore a two part procedure, of setting the parallel port to obtain the correct switching sequence before sampling the three inputs of the analog port and converting the analog readings to calibrate values before recording the required information on disc. This was performed by the test equipment recording program (SOL) which is capable of carrying out repeated sampling over an indefinite period, although in practice a run of 6 hours was found to be sufficient.

The order in which the readings were taken was as follows:-

	FIRST	SECOND	THIRD	FOURTH
INPUT 1.	T_3-T2	T2-T1	T3-T2	T2-T1
INPUT 2.	T4	T2	T4	T2
INPUT 3.	Vp	Ip	Vo	E

The calibration of the recording equipment was carried out under experimental conditions. The bridge supply voltage and heater voltage and current were compared with readings from a multi-meter which gave an accuracy of 0.5%. All the temperatures were calibrated using mercury in glass thermometers incremented in tenths of a degree, this was achieved by measuring the inlet and outlet water temperatures in a closed system using the constant water bath. The solarimeter had previously been factory calibrated. Therefore the calibrations used for the recording of the results were as follows:-

T_2-T1	3.30 Cv^{-1}.
T_3-T2	3.30 Cv^{-1}.
T_2	20.70 Cv^{-1}.
T_4	20.70 Cv-1.
E	0.0213 $Wm_{-2}v$-1.

POWER $4.92 \times 10^{-7}\ WV^{-1}I^{-1}$

A cycle of results, including pauses before each reading to obviate any switching fluctuations, takes in the region of four seconds. These readings are then averaged over 20 cycles before being written to disc. Therefore a set of readings is recorded on disc approximately once every eighty seconds.

The program SOL can be found in appendix D.

5.5 THE EXPERIMENTAL RESULTS

5.5.1 INTRODUCTION

Once the results were on disc consideration was given to the method of presentation. The program RESOUT was compiled which could list the recorded values for any of the recorded data sets. From these listings an appreciation of the fluctuation and range of values could be obtained. An example of a set of results (RES8) from an experimental run can be found in appendix D. The data being rather cumbersome to assess has been presented in a graphical form. The data was used to compile two graphs of related interest, the first demonstrates the changing nature of efficiency with heat loss, and the second the effect of insolation on the energy gained by the collector. Since all the sets of results are of such a repetitive nature computer programs have been written to graphically portray the results. Also included is an evaluation of the radial and axial solar beam incident angles so as to monitor their effect on collector performance.

5.5.2 THE SOLAR INCIDENCE ANGLE

As the sun moves across the sky the incident angle the sun makes with the collector changes both radially and axially. These angles {ref.5.2} can be calculated by knowing the time of day, direction and tilt of the collector, as shown in Fig.5.3.

COLLECTOR INCLINATION

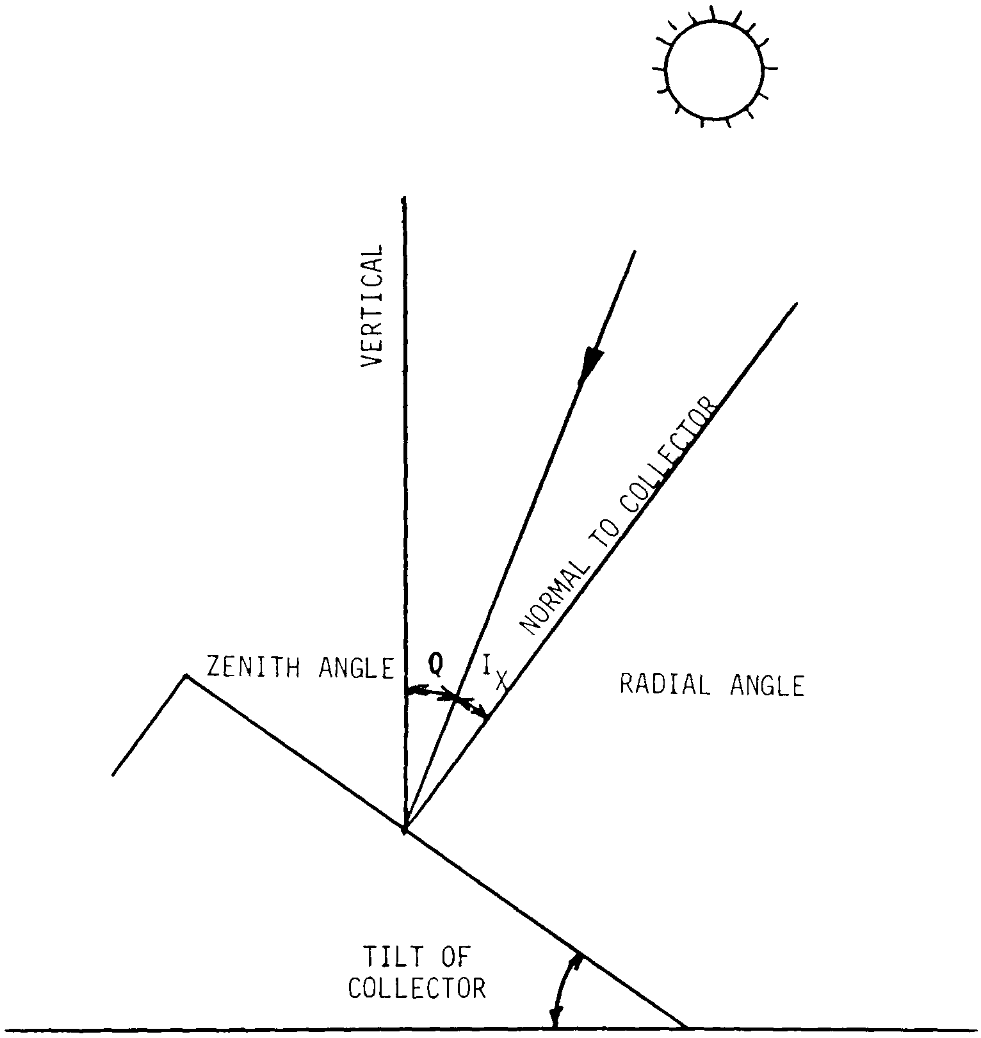


Fig. 5.3

The radial angle Ix and the axial angle Iz, as defined in Fig.5.4, can be evaluated once the tilt and azimuth angles of the collector have been set. The angles used for this evaluation are defined as:-

L latitude (north positive). The latitude for Cardiff Britain is approximately 50^{o}.

D declination. The angular position of the sun at solar noon with respect to the plane of the equator (north positive).

G Surface azimuth angle. (South East in this case: $+45^{o}$).

Q Zenith angle. The angle between the solar beam and the vertical, shown as angle (bon).

H Hour angle. Solar noon being zero and each hour equaling 15^{o}.

W Relative surface azimuth angle. The angle between the solar beam and the transverse plane (cross section of the collector) shown as angle (fog).

$$W = H - G = H - 45$$

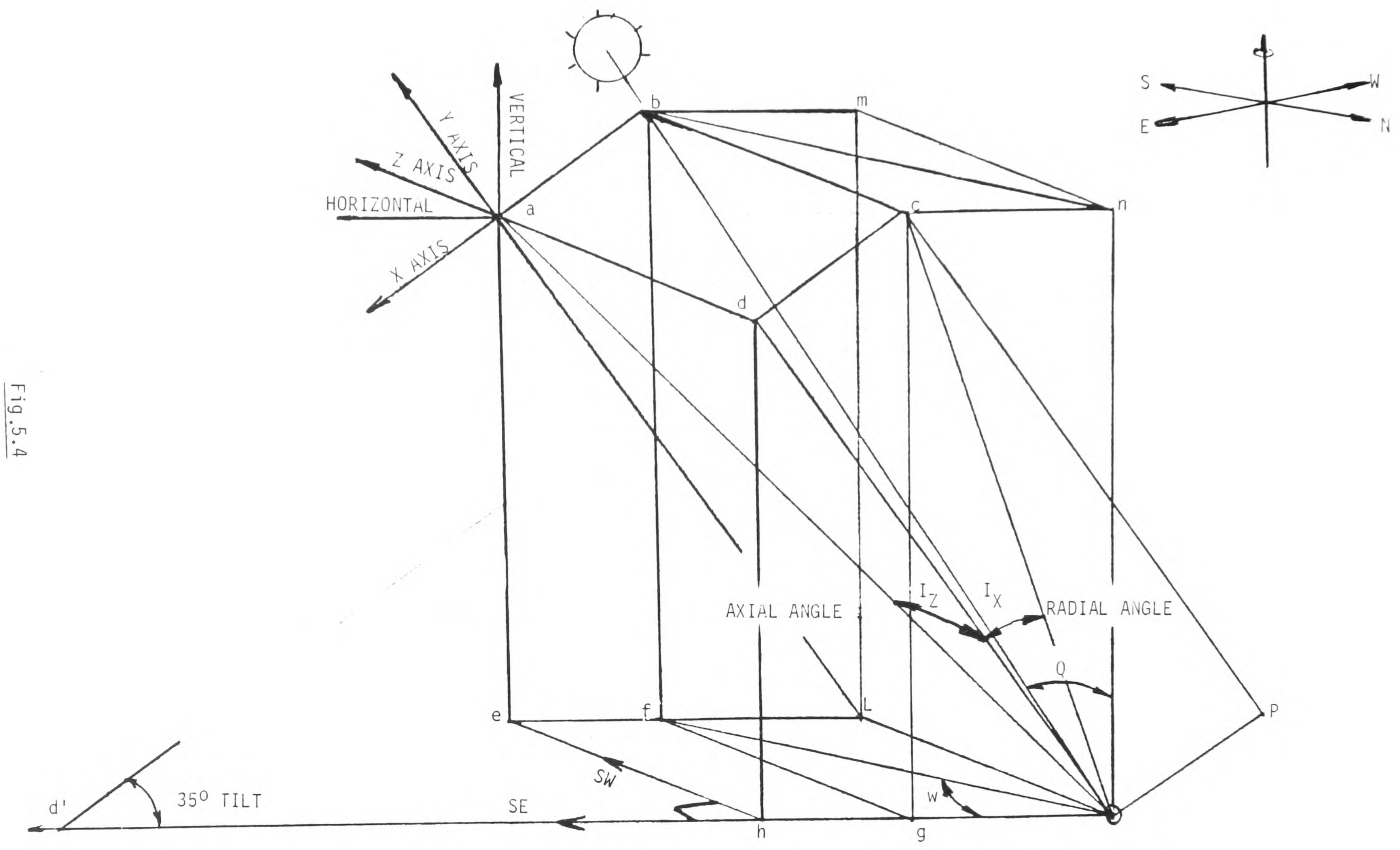
The declination D can be found from the following equation {ref.5.2} where N is the day in the year:-

$$D = 23.45 \sin[360(284 + N)/365]$$

This was found to be $\simeq 22^{o}$ for June 1st. and the zenith angle is defined as:-

$$\cos Q = \sin D \sin L + \cos D \cos L \cos H$$

The tilt of the collector was arranged so as to give the least radial angle whilst the results were taken. The axial angle reduces to zero when the relative surface hour angle is zero and



THE EVALUATION OF THE RADIAL AND AXIAL ANGLES OF THE SOLAR BEAM

Fig.5.4

since the collector is facing in a south easterly direction this occurs at 0900 hours. This suggests that experimental recording should be carried out at around this time in the morning to reduce 'end effects' {ref.5.3} on the performance of the collector. For instance if the axial angle reaches $\pm 45^{o}$ (3 hours from its zero position) the subsequent end losses are 30% of the collector area while the increased path length of the solar beam causes an extra 10% absorption in the Hyvis.

The zenith angle at 0900 hours and at solar noon on June 1st was calculated to be 44^{o} and 28^{o} respectively from the vertical, therefore the collector tilt was set at 35^{o}.

By considering Fig.5.4 the radial and axial solar incident angles can be evaluated from the following derived equations:-

If 'ob' is considered to be of unit length then:-

$$on = \cos Q$$

$$bn = \sin Q$$

$$og = of * \cos W = bn * \cos W = \sin Q \cos W$$

$$gf = of * \sin W = bn * \sin W = \sin Q \sin W$$

$$gd' = cg * \cot 35 = on * \cot 35 = \cos Q \cot 35$$

$$od' = og + gd' = \sin Q \cos W + \cos Q \cot 35$$

$$od = od' * \sin 35 = \sin Q \cos W \sin 35 + \cos Q \cos 35$$

Also:-

$$\tan(con) = cn/on = og/on = \sin Q \cos W / \cos Q = \tan Q \cos W$$

$$\tan(aod) = ad/od = gf/od$$

$= \sin Q \sin W /(\sin Q \cos W \sin 35 + \cos Q \cos 35)$

and where:-

$$Ix = 35^{o} - \text{angle}(con)$$

$$Iz = \text{angle}(aod)$$

we have:-

$$Ix = MOD[\ 35^{o} - \tan^{-1}[\tan Q \cos W]$$

$$Iz = MOD[\tan^{-1}(\sin Q \sin W /(\sin Q \cos W \sin 35 + \cos Q \cos 35))]$$

From the subsequent graphs of radial and axial angles for the above collector position it can be seen that the radial angle is decreasing from 20^{0} at 0745 to a zero at about 1005 and then increases but remains under 20^{o} for the rest of the morning. From consideration of both radial and axial angles the recording period should be limited to between 0830 and 1030 solar time.

5.5.3 THE COLLECTOR PERFORMANCE

The collector efficiency n and the unit temperature differential with respect to insolation (DT/E) can be evaluated from the recorded data as defined in section 5.2.2. A graph of the variation of these quantities has been charted for each experimental run. To give an idea of the responce time of the collector to changes in insolation its level was also plotted on the same graph. An estimate of the collectors steady state values was then obtained by a careful consideration of these three functions. The program EFFY (appendix D) was written to necessitate this objective. To smooth out the oscillatory nature of the graph it was necessary to average the recorded data over a twenty minute intervals.

5.5.4 ENERGY GAINED BY THE SYSTEM

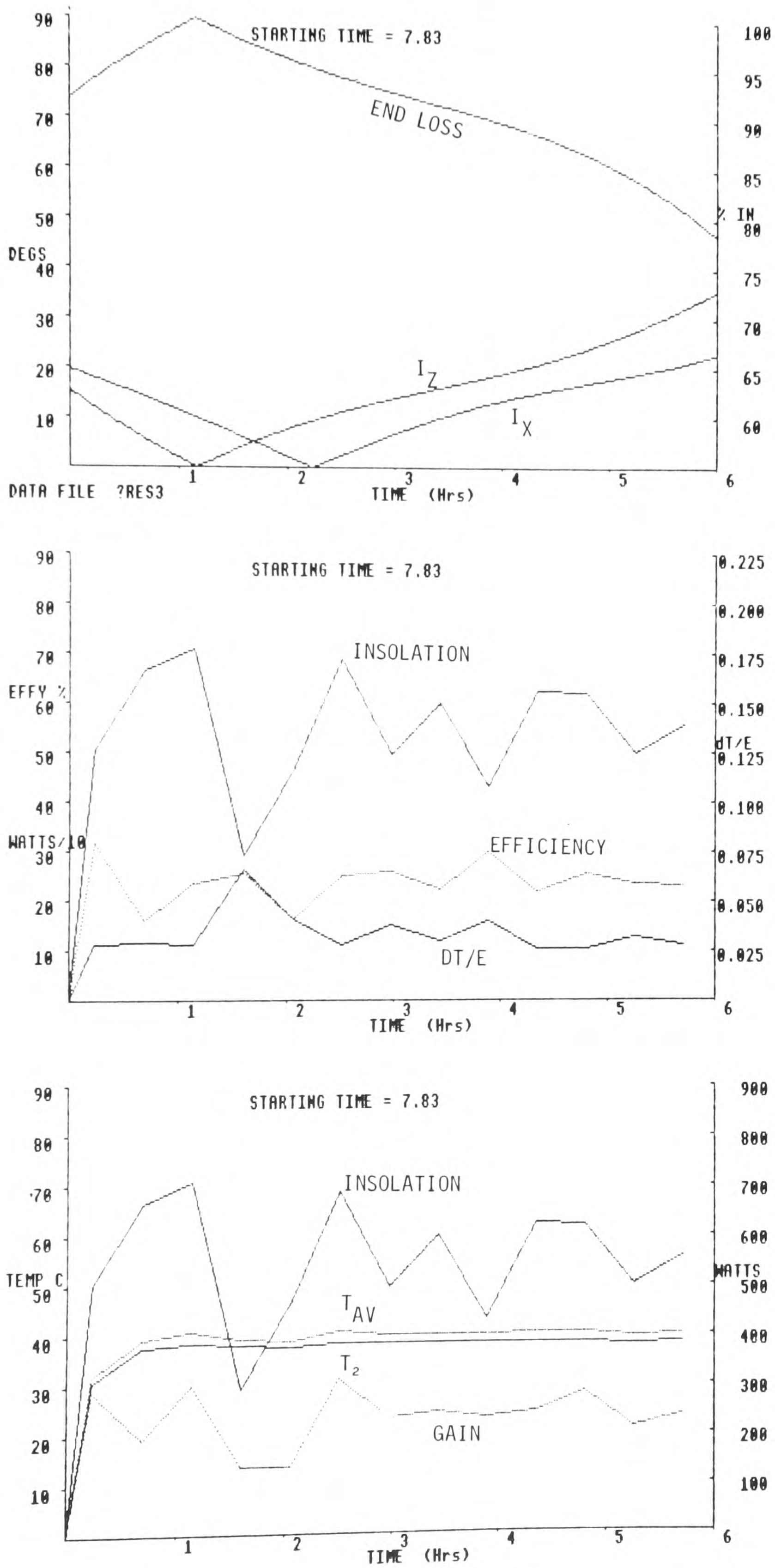
The energy gained by the transfer fluid is related to the amount of energy that is incident on the collector. It was therefore necessary to evaluate how these two important variables are related, and in particular how the time constant of the collector effects the time lag between them. A graph of energy gain and insolation was plotted against time, with both the inlet and average receiver temperatures superimposed on the graph. From this graph the performance of the collector can then be assessed for different input temperatures. The program AGAIN which plots these functions, defined in section 5.5.2 can be found in appendix D which as before are averaged over twenty minute intervals.

5.5.5 GRAPHICAL PRESENTATION OF EXPERIMENTAL RESULTS

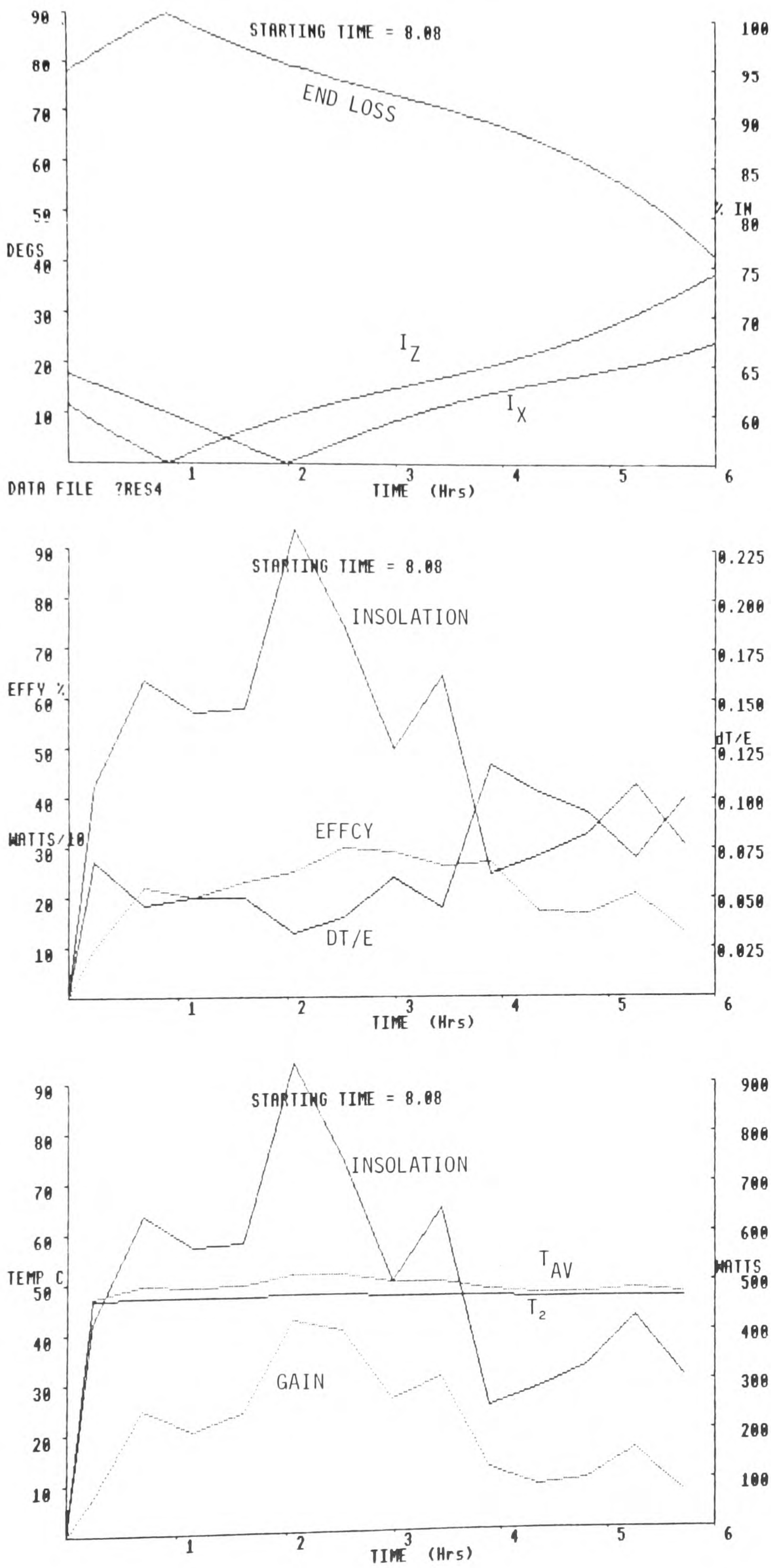
The graphs depicted in sections 5.5.2, 5.5.3 and 5.5.4 have been plotted for data sets from experimental runs and are shown in GRAPH 5.1 - GRAPH 5.5. From these graphs values of efficiency and unit temperature rise with respect to insolation (DT/E) have been chosen at points were the collector best demonstrates a steady state. To assist in its detection the following assumption has been used:-

> Since the receiver and ambient temperatures are approximately constant throughout an experimental run the temperature gradient at the receiver can never be less than when at the steady state. Therefore its heat loss is smallest and efficiency greatest for the steady state condition. This implies that a steady state for the collector is best demonstrated at its maximum efficiency positions. However for a collector with a long time constant this condition is rarely achieved and its efficiency is always less than what it would be for a steady state. Also, values chosen at times of falling insolation levels could have a proportion of their energy gained from the thermal mass of the collector as opposed

THE GRAPHICAL PRESENTATION OF EXPERIMENTAL RESULTS.

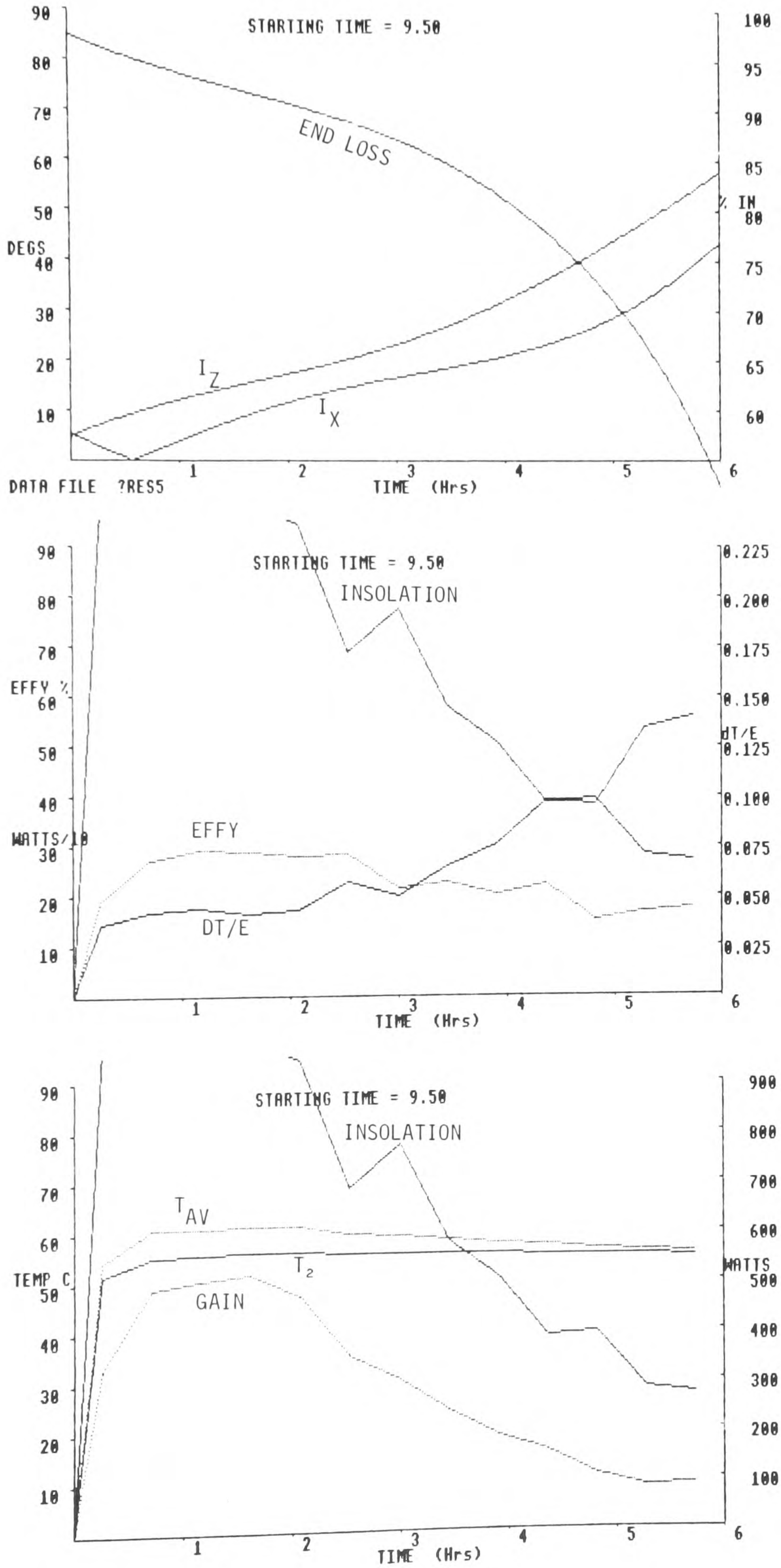


GRAPH 5.1



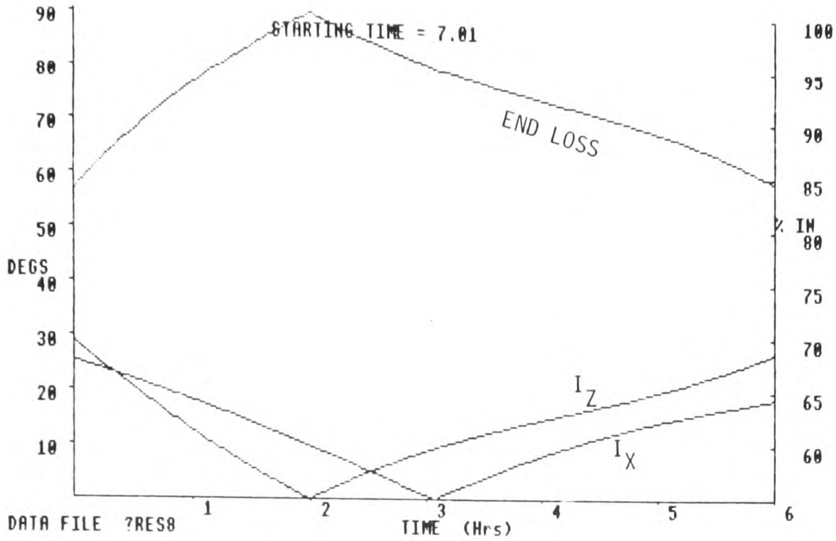
GRAPH 5.2

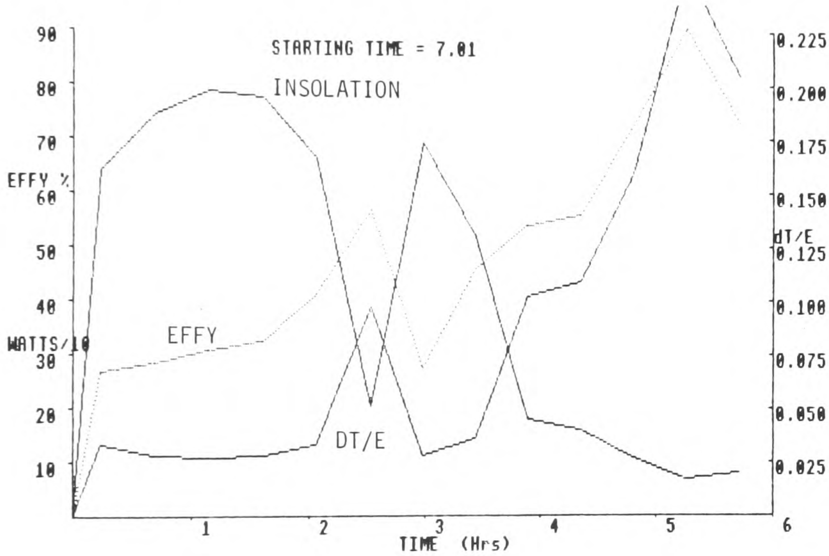
THE GRAPHICAL PRESENTATION OF EXPERIMENTAL RESULTS.

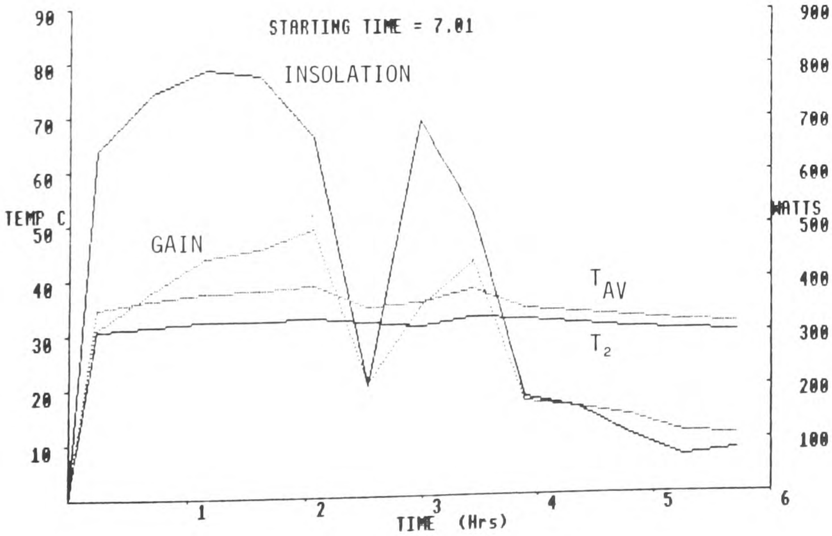


GRAPH 5.3

THE GRAPHICAL PRESENTATION OF EXPERIMENTAL RESULTS.

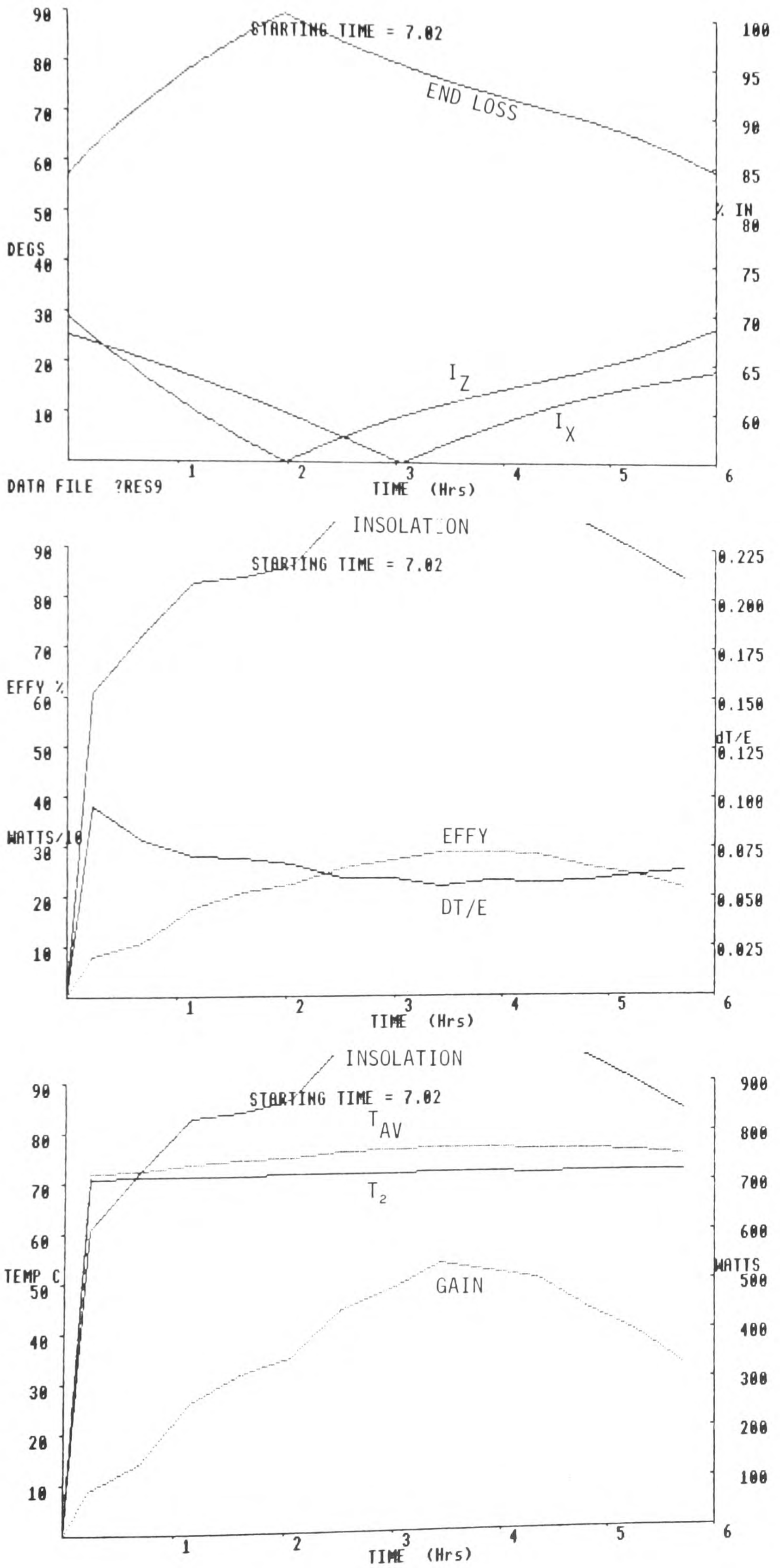






GRAPH 5.4

THE GRAPHICAL PRESENTATION OF EXPERIMENTAL RESULTS.



GRAPH 5.5

THE GRAPHICAL PRESENTATION OF EXPERIMENTAL RESULTS.

to direct insolation. This could cause a large error between the recorded efficiency and the steady state value if the Hyvis was not in a steady state. This is of particular importance at low input temperature where the thermal mass effect could produce inflated efficiencies.

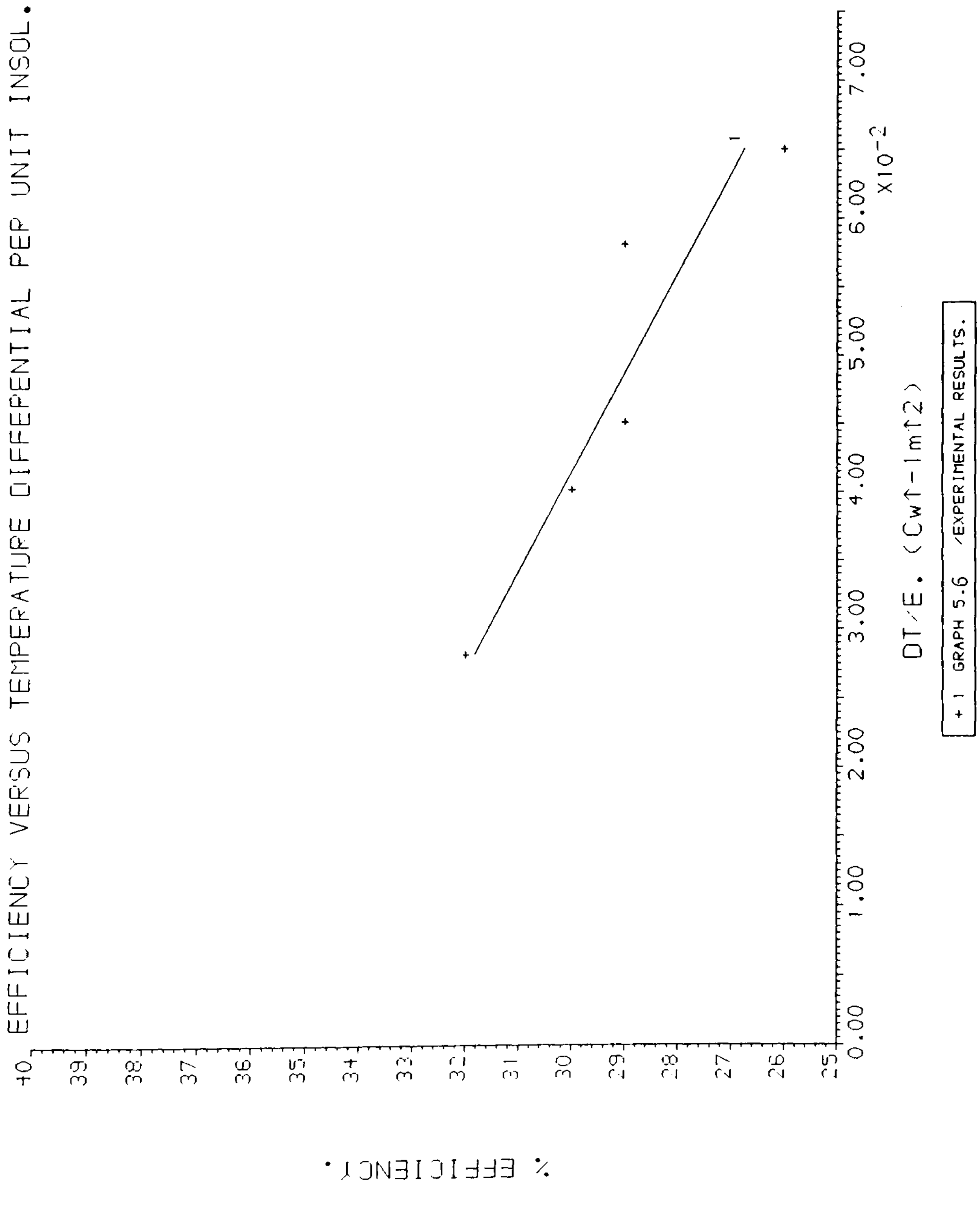
It is also worth considering the beam incident angle as outlined in section 5.5.2 as this also effects the efficiency.

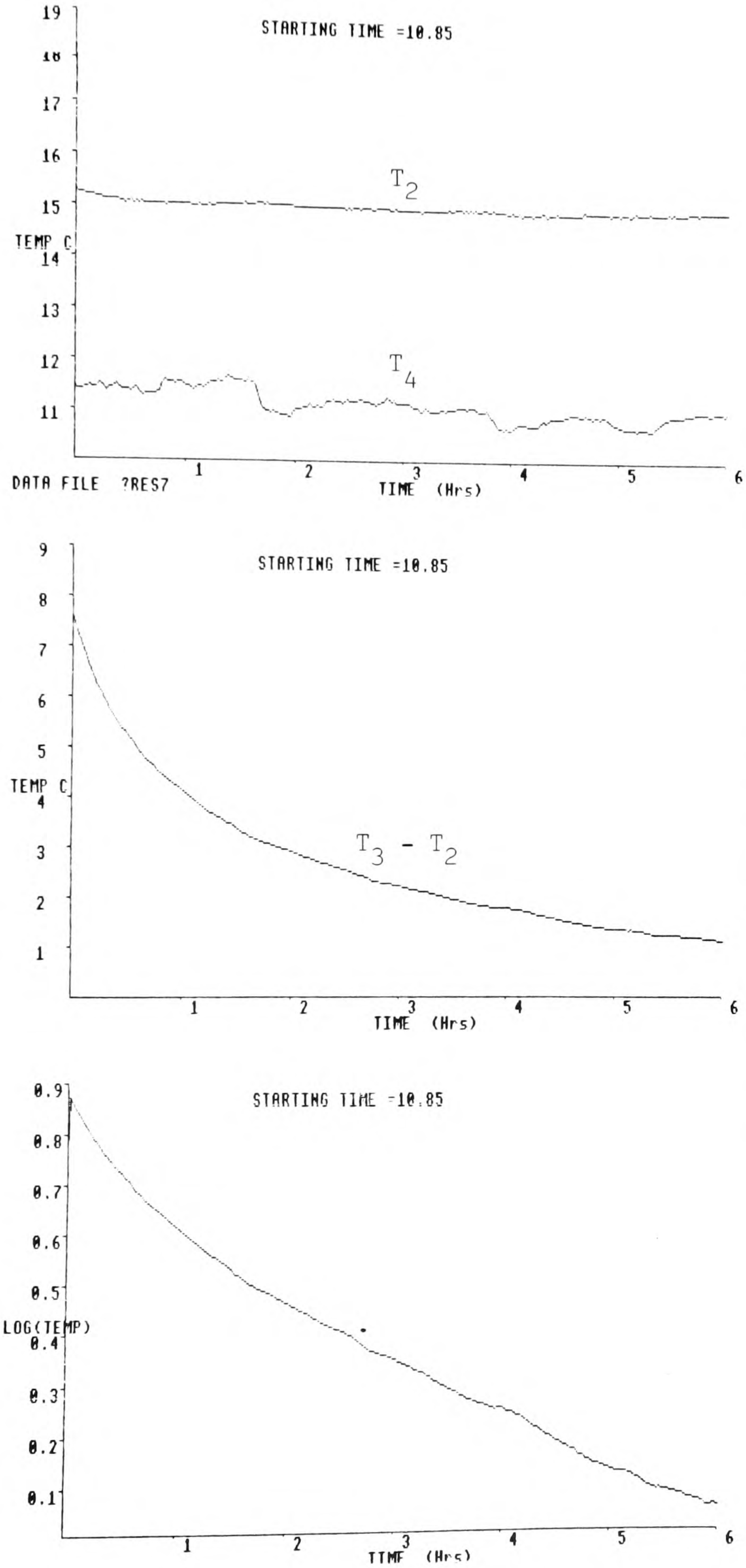
The values obtained from the data sets are as follows:-

GRAPH	DATA SET	EFFICIENCY (CW-1m2)	DT/E	SOLAR TIME
5.1	RES3	26%	0.065	1050
5.2	RES4	30%	0.040	1010
5.3	RES5	29%	0.045	1045
5.4	RES6	32%	0.028	0835
5.5	RES7	29%	0.058	1100

From these coordinates the graph of efficiency against temperature differential per unit insolation (DT/E) has been constructed and is shown in GRAPH 5.6.

The time constant of the collector has been experimentally evaluated using the same apparatus working under different operating conditions. The collector was preheated by the transfer fluid circulating at 60C for 24 hours prior to recording. The bath water was then changed and held at 15C throughout the experiment. By evaluating the rate at which the collector cooled during the night it was possible from newtons law of cooling to obtain the time constant being the rate of logorithmic change in temperture with respect to time as demonstrated by GRAPH 5.7. From this graph the time constant was found to be approximately 10 hours.


EFFICIENCY VERSUS TEMPERATURE DIFFERENTIAL PER UNIT INSOL.
% EFFICIENCY.
40
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
X10⁻²
DT/E. (Cw↑-1m↑2)
+ 1 GRAPH 5.6 /EXPERIMENTAL RESULTS.



Graph 5.7

THE GRAPHICAL PRESENTATION OF THE COLLECTOR COOLING EXPERIMENT

REFERENCES

5.1. ASHRAE. Methods of Testing Solar Collectors Based on Thermal Performance. 93-77 (1977).

5.2. J.F.Duffie and W.A.Beckman, Solar Energy Thermal Processes (1974).

5.3. S.M.Jeter and D.I.Jarrar and S.A.Moustafa, Geometrical Effects On The Performance Of Trough Collectors. Solar Energy 30,109 (1983).

CHAPTER 6

CONCLUSION AND FUTURE DEVELOPMENTS

6.1 INTRODUCTION

It is now possible to set out the findings of this project and to compare the results of the numerical analysis with those derived from the experimentation. It will be seen from the following information that in some aspects the simulation and the experimentation are in close agreement while in others an explaination for the variation between the two methods is offered. It is important to realise that the two elements of this investigation have been carried out to assist in the overall development of the collector and in many aspects do not overlay. It is therefore only appropriate to compare those aspects which are common to both sections. From these comparisons there is much to be gained with a vue to future developments and optimisations as well as a greater depth of understanding of the inherent problems of collector design and construction. The most relevent parameters for which comparisons are offered are maximum efficiency, the thermal loss coefficient and the time constant of the collector. Included also is a comparison with other commercial collectors which attempts to put into perspective the significance of this new family of concentrating solar traps. Finally there is an appraisal of the project which analyses whether the original aspirations of the system have been achieved with suggestions for further improvements which could be undertaken.

6.2 CONCLUSIONS OF THE OPTICAL EFFICIENCY

It is perhaps worthwhile comparing the ray tracking simulation with another commonly used collector geometry, the 'Ideal' Compound Parabolic Collector (CPC) {ref.6.1}. From the results of the simulation for the optimised Concentrating Solar Trap

(CST) Collector it is apparent that the title of 'Ideal' for the CPC is misleading. For a CPC with a concentration ratio of C the collection of diffuse radiation is 1/C for isotropic radiation, this does not compare favourably with the CST. An 'Ideal' CPC with the same magnification of 2.97 {ref.6.6} would accept 33.70% of diffuse radiation whereas the CST accepts 38.12% at the receiver. Also, refering to beam insolation on a CPC {ref.6.2}, 'for which no beam radiation is assumed to be accepted at angles greater than the acceptance angle', is again less than for the CST. The simulation predicting rays of up to 50^{o} to the optic axis still reaching the receiver, some 20^{o} more than the acceptance half angle for the CPC. However this is merely a comparison of the optimised collector's parameters and may not reflect the same conclusion for other geometric ratios. It is however apparent that a more detailed comparison, without the trap, may reveal a new class of concentrating collector that out performs the CPC. Any new simulation should also include other types of curvature, such as a 'Trumpet' PCST from which I would expected a better efficiency than is possible from this cylindrical design.

6.3 A COMPARISON OF THE SIMULATED AND EXPERIMENTAL RESULTS

From the simulation carried out in chapters 2 and 3 predictions for both the steady and unsteady state conditions have been evaluated. From the steady state results values of the maximum efficiency and thermal loss coefficient have been determined whilst the time constant of the collector has been found from the unsteady state simulation.

From the graphs of 3.1 and 3.3 it can be shown that the simulation prediction are:-

Maximun efficiency	72%
Thermal loss coefficient	1.655 $m^{2}CW^{-1}$

Time constant 13 hours.

The experimental results set out in chapter 5 conclude the following results:-

Maximum efficiency 36%

Thermal loss coefficient 1.376 m^2CW^{-1}

Time constant 10 hours.

It could be gathered from these results that the two sets have very little in common especially when the experimental maximum efficiency is exactly half of the simulated value. This however can be partially explained by the inherent assumptions made in the simulation. The reduced efficiency is the direct result of the following factors.

1. The simulation of optical efficiency did not account for any absorption of the glass cover. This was not a serious ommission of the simulation as it would be approximately constant for all collector shapes considered. However it has been found experimentally that the plate glass used in the collector construction has a transmittance of 82% with two reflections. When used on the collector there will only be one reflection and therefore it can be assumed to have a transmittance of 86%.

2. The simulation uses an inaccurate value for the solar transmittance in Hyvis, as has been previously explained in chapter 4. Since the average path length of a ray as it passes through the Hyvis is 0.2m, then from GRAPH 4.7, the experimental results of transmittance of Hyvis, it can be deduced that an extra 20% of the solar energy is absorbed in the Hyvis that in the simulation reached the receiver.

3. The simulation did not account for solar intensity components in the sagital (z) axis which has the effect of

increasing the length of the solar path through the Hyvis. This has the effect of reducing the transmittance by a maximum of 2% during the recording periods.

4. The simulation does not account for 'end-effects' {ref.6.3} due to solar intensity components in the sagital axis. If the end plates are non-reflecting this occurs at both ends of the collector. However there is absorption in the Hyvis at the end furthest from the sun but this has an insignificant effect on the overall performance. End-effects or shading can cause a considerable reduction in the effective collector area. It is estimated that this effect accounts for a 11% reduction of the incident solar energy at 1100 when most of the steady state efficiencies were recorded.

Therefore the maximum efficiency prediction for the simulation should be modified as follows. Only 89% of the incident radiation can be considered because of 'end effects', of this 86% penetrated the glass cover. Of the 76% remaining 50% (72-20-2) reaches the receiver, giving a maximum efficiency of 38 %. The difference between the experimental and simulated values is now considerably reduced. The remaining 2% variation is well within the expected experimental tolerance but will include errors in the collector geometry caused in construction and for the approximate psuedo-steady state values used for the graph.

The comparisons of the Thermal loss coefficient is not as critical on energy generation as the optical efficiency is on Transmittance and therefore much closer values are to be expected. The value of 1.376 m^2CW^{-1} for the experimental thermal loss coefficient compared to 1.655 m^2CW^{-1} for the simulation is exceptable because of the greater energy absorption in the Hyvis for the experiment.

These results demonstrate a very favourable aspect that is enjoyed by the collector and was an original requirment of the design, that the collector would be able to operate in less favourable conditions Unfortuneately this has been at the expense of the transmittance absorptance product, a price to high to pay.

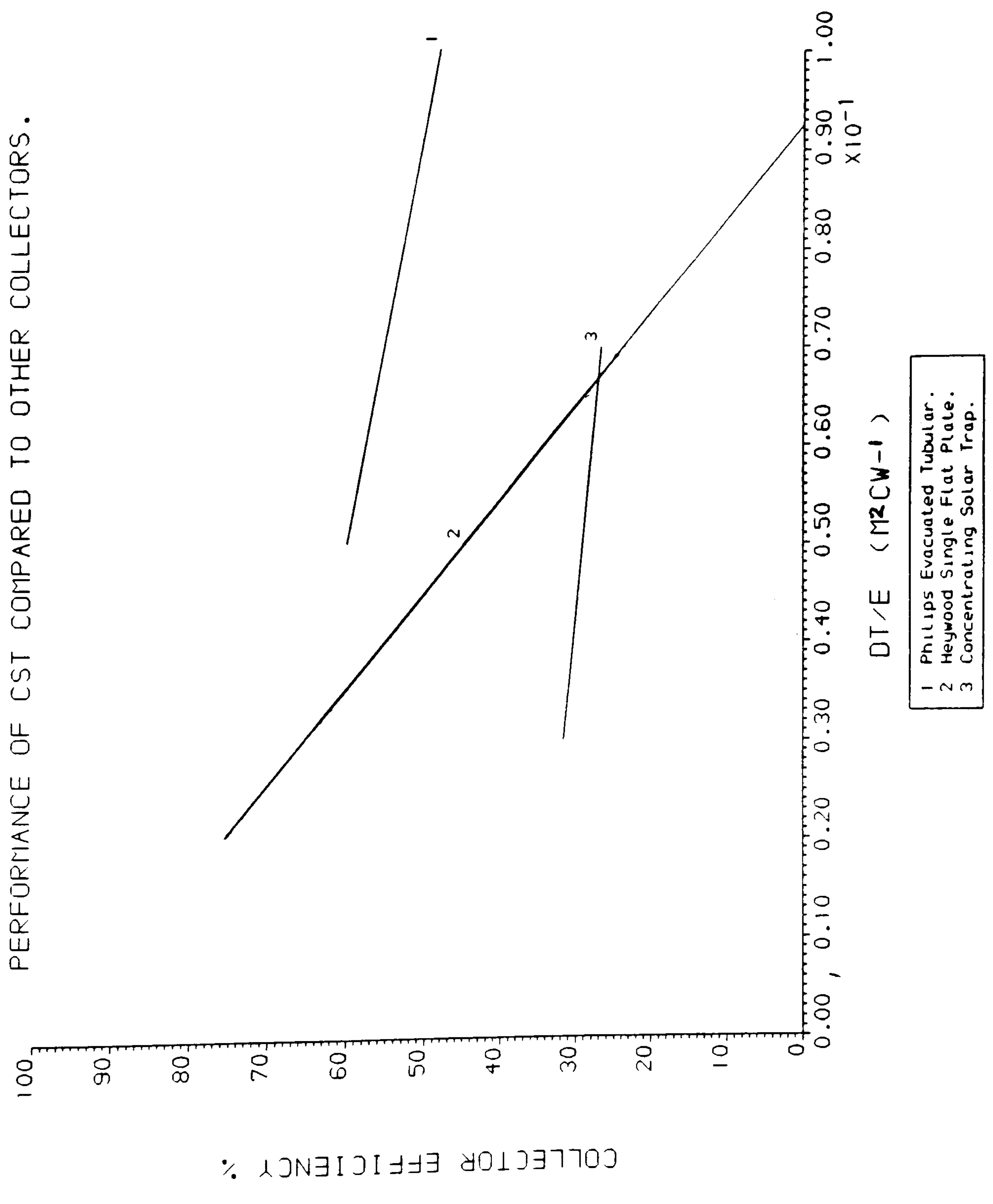
The simulation method of determining the time constant has an inherent error due to the shear number of calculations required with such a small time step, the emormous length of time required for its execution has mean't that this value has not been checked for convergence. Likewise, the experiment used for recording the cooling of the collector incurred larger experimental errors than is normally the case because of the low temperature rise of the transfer fluid. However it can be infered that the time constant of the collector is of the order of 10 hours.

The method of determining the steady state values for the collector could be improved by using the transient collector performance test method {ref.6.4} defined in the British Standards Institution Draft For Development DD77:1982 but this seemed in appropriate for this initial investigation, however this should be considered in any subsequent evaluation.

6.4 A COMPARISON WITH OTHER COLLECTORS

Although it may be possible to improve the collector efficiency by changing the trap material or glass cover, this comparison must direct itself to the actual collector built and does not consider the collector potential which is dealt with in section 6.5.

GRAPH 6.1 {ref.6.5} shows the comparison with two commercially available collectors, the Philips Evacuated Tublar Collector and the Heywood Single Glazed Collector. It is not difficult to conclude which is the best system from these steady state conditions with the concentrating solar trap being by far the worst.


PERFORMANCE OF CST COMPARED TO OTHER COLLECTORS.
COLLECTOR EFFICIENCY %
DT/E (M2CW-1)
X10-1
1 Philips Evacuated Tubular.
2 Heywood Single Flat Plate.
3 Concentrating Solar Trap.

Graph 6.1

It can be seen that the Philips collector, which is only one of a number of evacuated tube type collectors, is by far the most efficient and may only be challenged with regards to low grade heat and cost per unit energy gained. At the low grade end of the market the single glazed unit is by far the most efficient and cheapest. From this graph the CST is only comparable with the Flat Plate Collector at the higher grade end of the graph, the cross over point coming at about 0.065 m^2CW^{-1} which for a temperature differential of 35C relates to a solar intensity of anything less than $500Wm^{-2}$. Although on cost the single glazed unit would be cheapest. This review although somewhat light hearted does suggest that from the original specifications for the collector there is scope for the collector especially in less favourable climatic conditions.

This comparison has only dealt with the steady state conditions of three vastly different collectors. It could be argued that a better comparison would be the energy output from equal apperature collectors operating in parallel over a long period of time. This with cost considerations could provide a more realistic picture of the overall performance characteristics of the collectors. Unfortuneately this has not been possible although the CST would be expected to do slightly better under long term testing due to its thermal storage capabilities.

6.5 IMPLICATIONS AND IMPROVEMENTS OF THE COLLECTOR

This study has undertaken the task of optimising the efficiency of a CST and although the resulting collector has not broken through any new barriors of collector performance there are many relavent facts and figures that have been gained from this study.

The performance of the CST is in close agreement with the simulation which showed promising results for a trap with a better transmittance. In this respect the collector does have potential although at the moment is propably not worth any commercial venture. The collector has shown however that collectors with low thermal loss are possible without the necessity of evacuation.

Before the status of this collector can be fully analysed a more detailed study of collector design and construction should be carried out. This development should address itself to the fundumental parameters highlighted by this initial study. It may be possible to improve the transmittance of the trap material or replace it with some form of transparent gel which is capable of withstanding the temperature range of the required collector.

There is also scope for the collector optimisation to be improved. An optimisation with more emphasis on optimum collector depth and a more detailed study of boundary curvatures would propably reveal a more efficient geometry. For example, if the collector used a high transmittance cover and reduced the depth of the collector to 10cm the maximum efficiency would increase to 49%.

In the overall concept of CST's it must be remembered that other types of geometries could be studied which could provide a better performance such as parabolic curves.
I therefore conclude that this study has only highlighted the need for further investigation.

<u>REFERENCES</u>

6.1. R.Winston, Principles of Solar Concentrators of a Novel Design. Solar Energy 16,89 (1974).

6.2. M.J.CARVALHO and M.Collares-Pereira and J.M.Gordon and A.Rabl, Truncation of CPC Solar Collectors and its effect on Energy Collection. Solar Energy 35,393 (1985).

6.3. S.M.Jeter and D.I.Jarrar and S.A.Moustafa, Geometrical Effects on the Performance of Trough Collectors. Solar Energy 30,109 (1983).

6.4. B.A.Rogers, On a Solar Collector Thermal Performance Test Method for Use in Variable Conditions. Solar Energy 33,117 (1984).

6.5. J.C.McVeigh, Sun Power An Introduction to the Applications of Solar Energy. ISBN 0 08 0208622.

6.6 A.Rabl, Comparison of Solar Concentrators. Solar Energy 18,93 (1976).

APPENDIX A

```
*
*PROGRAM        :RWE9.FOR
*WRITTEN BY     :R.W.ELLIOTT.

      DOUBLE PRECISION  A,B,C,G,F,X,Y,X1,X2,Y1,Y2,YT,XI,XX,CK,Z       !THESE VARIABLES USE VERY HIGH ACCURACY SO AS TO
      DOUBLE PRECISION  DIS,R2,RT,RI,RR,RAY,FNQ,FSNQ,RFFM,RFFC         !OVERCOME THE PROBLEM OF RAYS WHICH PASS NEAR
      DOUBLE PRECISION  COSD,ASIN,SIND,TAND,DATAN,DSQRT,DABS,RAYR,DSIN,DCOS      !BOUNDARIES OR BOUNDARY INTERCEPTS.
      DIMENSION ANSWER(13,8)                          !CREATE TWO 3 DIMENSIONAL ARRAYS  WHICH ARE 13X8 AND 20X15.
      INTEGER*4      D,TT,J,I,IX
      OPEN(UNIT=32,NAME='RWE9.DAT',TYPE='NEW')        !Data file to store energy generation array.

      U=1.526                                                  !THE REFRACTIVE INDEX OF THE 'HYPO 2000'.
      N=1
      S=0                                              !S IS A PARAMETER FOR LATERAL MOVEMENT OF THE SIDE SURFACES.
      L=0                                              !L IS A PARAMETER FOR CHANGING THE ANGLE OF THE LIGHT RAYS.
      P=1000000                                               !ANY RAY LONGER THAN 10 METERS IS IGNORED (HARDLY ANY).
      DO 100 IT=2,10                                   !A LOOP TO CHANGE THE RADIOUS OF THE TOP SURFACE.
      R1=5*2**IT-10                                    ! -F IS THE CENTRE OF THE TOP SURFACE.
                                                       !R1 IS THE RADIOUS OF THE TOP SURFACE.
      DO 200 IS=2,10                                   !A LOOP TO CHANGE THE RADIOUS OF THE SIDE REFLECTING SURFACE
      G=6-4*2**IS                                      !G IS A PARAMETER FOR THE SIDE REFLECTING SURFACES.
      DO 700 IH=15,9,-1                                       !A LOOP TO REDUCE THE HEIGTH, WITHOUT CHANGING THE RADIOUS.
      H=IH                                             !THE Y AXIS INTERCEPT OF THE TOP SURFACE.
      F=R1-H                                           !ADJUSTMENT OF F WHEN TOP SURFACE IS LOWERED.
      FF=(-F)                                          !THE Y COORDINATE OF THE CENTRE OF THE TOP SURFACE.
      DO  600  S=1,3,1                                        !A LOOP TO MOVE OUT THE SIDES WITHOUT CHANGING THE RADIOUS.
                                                       !PARAMETER FOR CHANGING THE SIDES CENTRE WITH SAME RADIOUS.
      R2=DABS(G)                                       ! R2 IS THE RADIOUS OF THE SIDE SURFACES.
      GG=R2+S                                          ! X COORDINATES OF THE CENTRES OF THE TWO SIDE REFLECTING
      GGG=(-GG)                                        ! SURFACES.
      IF(DABS(F).LE.0.0001)  GO TO  700                !IF THE CENTRE OF THE TOP IS ON X AXIS EQUATIONS ARE UNTRUE.
      CK=(H**2+2*F*H-S*(2*G-S))/(2*F)                  !THE CONSTANTS IN THE QUADRATIC EQUATION THAT WILL EVALUATE
      A=1+(G-S)**2/F**2                                !THE INTERCEPT BETWEEN THE SIDE SURFACES AND THE TOP SURFACE
      B=2*(G-S)*(CK+F)/F
      C=CK**2+2*F*CK-H**2-2*F*H
      IF(B**2-4*A*C)200,2,2                            !IF THE DISCRIMINANT IS NEGATIVE THEN NO INTERCEPT.
2     CALL QUADRT ( A,B,C,X)                           !SUBROUTINE TO EVALUATE A QUADRATIC ; AND GIVE +VE ROOT.
      IF(F.GT.0)  X=(-B-DSQRT(B**2-4*A*C))/(2*A)       !IF CENTRE OF TOP SURFACE IS NEGATIVE WE NEED OTHER ROOT.
      Y=(G-S)*X/F+CK                                   ! Y COORDINATE OF THIS INTERCEPT.
      IXQ=X/2                                          !CONDITION THAT CONCENTRATION IS > A FACTOR OF TWO.
      IF(IXQ.LT.S)  GO TO 700                          !IF SIDES ARE TO FAR APART CHANGE THE SHAPE.
      WRITE(32,78)                                            !PRINT OUT OF THE REFERENCES AND COORDINATES OF THIS SHAPE
      WRITE(32,79)FF                                   !IE. THE CENTRES, RADII AND INTERCEPTS.
      WRITE(32,80)
      WRITE(32,81)GGG,GG
      WRITE(32,50)R1
      WRITE(32,51)R2
      WRITE(32,52)
      X=(-X)
      WRITE(32,53)X , Y
      X=(-X)
      WRITE(32, 54)X , Y
      DO 310 IQ=1,IXQ,1                                !THIS LOOP DETERMINES THE WIDTH OF THE COLLECTOR PLATE.
      Q=IQ                                             !Q IS THE RIGHT HAND X COORDINATE OF THE COLLECTOR PLATE.
      IF(Q.LT.S)  GO TO  310                           !TEST IF COLLECTOR WIDTH IS < DISTANCE BETWEEN SIDES.
      QQ=(-Q)                                          ! QQ IS THE LEFT HAND X COORDINATE OF THE COLLECTOR.
      YT=(S*(2*G-S)-2*(G-S)*Q-Q**2)
      YT=DSQRT(YT)                                     !THE Y COORDINATE OF THE COLLECTOR PLATE.
      ZQ=Q-QQ                                          ! ZQ IS THE WIDTH OF THE COLLECTOR.
      WRITE(32,75)                                            !PRINT THE REFERENCES FOR THE COLLECTOR.
      WRITE(32,76)Q,QQ
      CALL VOLUME (R1,R2,X,Y,Q,YT,F,S,VOL)             !SUBROUTINE TO OBTAIN THE INTERNAL VOLUME OF THE COLLECTOR.
      L=0                                              !L IS A PARAMETER FOR THE DIFFERENT INCIDENCE RAYS.
      DO 300 LQ=240,300,5                              ! TO CHANGE THE ANGLE AT WHICH THE RAYS ENTER THE COLLECTOR.
      REF=0                                            !REF IS THE NUMBER OF REFLECTIONS. AT START SET TO ZERO.
      TOTENY=0
      IX=99*X                                          !RANGE OF INCIDENCE RAYS ON THE TOP SURFACE MAGNIFIED BY 99.
      XZ=0.9999*X                                      !CONDITION : COORDINATE FOR LIMIT OF  BOUNDARY ACCURACY.
      L=L+1                                            !FIRST VALUE OF L FOR FIRST CONSIDERED INCIDENCE ANGLE.
      ANSWER(L,1)= LQ                                  !ANGLE OF INCIDENCE FOR EACH  VALUE OF L.
```

```
      ANSWER(L,2) = 0                          !NUMBER OF RAYS INCIDENT ON TOP SURFACE BEING CONSIDERED.
      ANSWER(L,3) = 0                          !NUMBER OF SIDE REFLECTIONS FOR THIS SHAPE AT THIS ANGLE.
      ANSWER(L,4) = 0                          !NUMBER OF TOTAL INTERNAL REFLECTIONS FOR THIS SHAPE AT THIS ANGLE.
      ANSWER(L,5) = 0                          !THE FRACTION OF INCIDENT ENERGY REACHING COLLECTOR AT THIS ANGLE.
      ANSWER(L,6) = 0                          !NUMBER OF RAYS REACHING THE COLLECTOR AFTER ABSORBTION LOSES.
      ANSWER(L,7) = 0                          !NUMBER OF RAYS INCIDENT REACHING THE COLLECTOR.
      ANSWER(L,8)=0                            !FRACTION OF INCIDENT RAYS REACHING THE COLLECTOR AT THIS ANGLE.
      DO 455 IXI=IX,(-IX),-1                   !A LOOP TO CONSIDER EACH RAY, LEAVING 1% OF WIDTH AT BOUNDARIES.
      XI=IXI                                   ! X COORDINATE OF INCIDENT RAY MAGNIFIED BY 100 TIMES.
      X1=XI/100                                ! X COORDINATE OF THE INCIDENT RAY. EACH RAY 1/100TH OF A CM APART.
      TRR=90                                   ! PARAMETER FOR TOTALLY INTERNALLY REFLECTED RAY. PRESET TO
                                               ! LARGE VALUE SO AS THIS CONDITION WILL NOT EJECT RAY UNLESS RESET
                                               ! BY TOTAL INTERNAL REFLECTING CONDITION.
      TIR=0                                    ! COUNTS THE NUMBER OF TIMES RAY TOTALLY INTERNALLY REFLECTED.
      TRAP=0                                   !CONDITION. IF TRAP=0 THEN RAY HAS NOT REACHED THE COLLECTOR.
      RLOP=0.1                                 !ASSUME 5.6% ABSORPTION IN FIRST 1MM. REFLECTION LOSSES TO BE ADDED.
      REF=0                                    !RESET NO OF REFLECTIONS TO ZERO FOR NEW RAY.
******************************************
*      RAY STARTING FROM TOP SURFACE     *
******************************************
      J=4                                      !IF J=4 THEN RAY IS ENTERING THE TOP SURFACE.
      D=1                                      !IF D=1 THEN RAY IS COMING FROM TOP SURFACE AND RAY MUST BE TESTED
                                               !FOR INTERCEPTION ON SIDE SURFACES BEFORE TESTING AT THE COLLECTOR.
      A=1                                      !PARAMETERS OF THE EQUATION FOR THE Y VALUE OF THE INCOMING RAY.
      B=2*F
      C=X1**2-H**2-2*F*H
1     CALL QUADRT (A,B,C,Y1)                   !Y1 IS THE Y COORDINATE OF THE STARTING POINT OF THE RAY.
      IF(X1.EQ.0) THEN                         !AT THIS POINT THE NORMAL 'FNQ' IS VERTICAL THEREFORE SET FNQ=90°
              FNQ=90                           !SET THE NORMAL OF THE TOP SURFACE TO 90°.
      ELSE                                     !RETURN TO PROGRAM TO CALCULATE THE REFRACTED RAYS ANGLE (RAY).
              FNQ=DATAN((Y1+F)/X1)             !THE NORMAL TO THE TOP SURFACE IN RADIANS ANTICLOCKWISE FROM X AXIS.
              FNQ=FNQ*180/3.141592653589793238 !THE NORMAL TO THE TOP SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS.
              IF(FNQ.LT.0)  FNQ=FNQ+180
      ENDIF
3     I=LQ-180                                 !I IS A PARAMETER FOR THE INCIDENT RAY.
      IF(I.LE.FNQ)  RI=FNQ-I                   !RI IS THE ANGLE OF INCIDENCE FOR THE INCOMING RAY.
      IF(I.GT.FNQ)  RI=I-FNQ
      IF(RI.GE.90)  GO TO  450                 !IF THE INCIDENCE ANGLE IS GREATER THAN 90' THEN COORDINATE IS IN SHADOW.
      RR=ASIN(SIND(RI)/U)                      !REFRACTED ANGLE IN RADIANS.
      RR=RR*180/3.141592653589793238           !REFRACTED ANGLE IN DEGREES.
      IF(I.LE.FNQ)  RAY=FNQ-RR+180             !RAY IS THE ANGLE THE LIGHT BEAM MAKES WITH THE X AXIS.
      IF(I.GT.FNQ)  RAY=FNQ+RR+180
      IF((RAY.EQ.90).OR.(RAY.EQ.270))  X2=X1   !IF RAY IS VERTICAL ITS SLOPE IS INFINITE SO PUT X2=X1.
                                               !IF RAY IS VERTICAL PUT X2=X1 AND FIND THE Y INTERCEPT.
      IF(RAY.EQ.90)  GO TO  12                 !IF RAY+90 ONLY INTERCEPT IS WITH THE TOP SURFACE.
      IF(RAY.EQ.270)  GO TO  17                !IF RAY=270 THEN RAY CAN ONLY BE COMING FROM THE TOP SURFACE,M
*********************************
*      RAY STARTING TREK        *
*********************************
33    RAYR=RAY*3.141592653589793238/180
      RFFM=DSIN(RAYR)/DCOS(RAYR)               !FIND THE SLOPE OF THE RAY  (RFFM).
      RFFC=Y1-X1*DSIN(RAYR)/DCOS(RAYR)         !FIND THE INTERCEPT OF THE RAY  (RFFC).
      IF((RAY.LT.90).AND.(J.EQ.2))  GO TO  88  !IF J=2 THEN RAY IS COMING FROM R.H.S. AND WITH RAY < 90'IT CAN ONLY
                                               !INTERCEPT WITH THE TOP SURFACE.
      IF((TT.EQ.1).AND.(D.EQ.0))  GO TO  9     !D=0 MEANS THE RAY MUST BE COMING FROM THE SIDE SURFACES. TT=1 MEANS
                                               !RAY < 180' THEREFORE IMPOSSIBLE INTERCEPT WITH COLLECTOR.
      IF(D.EQ.1)  GO TO  21                    !TEST THE SIDE SURFACES BEFORE THE COLLECTOR FOR RAY INTERSECTION
                                               !BECAUSE RAY IS COMING FROM  THE TOP SURFACE.
*****************************************
*      RAY INTERCEPT WITH COLLECTOR     *
*****************************************
19    X2=(-RFFC/RFFM)                          !X2 IS THE RAY INTERCEPT ON THE X AXIS.
17    IF((DABS(X2)-S).LT.0.0001)  THEN         !THE RAY ENTERS THE COLLECTOR.
            Y2=YT                              !FIND THE Y COORDINATE OF THE RAY ON THE COLLECTOR SURFACE.
            IF(X2.GT.S)      THEN              !IF THE NEW X COORDINATE IS OUTSIDE THE COLLECTOR RANGE.
                    X2=S-0.0001
            ELSE
                    IF (X2.LT.(-S))THEN        !USE ITS LIMITING VALUES.
                    X2=0.0001-S
                    ENDIF
            ENDIF
```

```
           TRAP=1                                 !TRAP=1 IS THE VARIABLE TO SHOW THE RAY HAS REACHED THE COLLECTOR.
           GO TO  14                              !NOW FIND THE TOTAL LENGTH OF THE RAY IN THE LIQUID.
      ENDIF
      X2=X1                                  !REPLACE X2 WITH ORIGINAL VALUE SINCE THIS VALUE IS INCORRECT.
      D=0
9     IF(J.EQ.1)  GO TO  44                  !RAY COMING FROM L.H.S. THEREFORE TEST FOR INTERCEPT ON R.H.S.
********************************
*     INTERCEPT L.H.S.         *
********************************
      A=1+RFFM**2                            !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
      B=2*RFFM*RFFC-2*(G-S)                  !THE L.H.S.  (LEFT HAND SIDE SURFACE).
      C=RFFC**2-2*(G-S)*S-S**2
      IF((B**2.LT.4*A*C).AND.(D.EQ.1))  GO TO  19      !NO INTERCEPT ON L.H.S. AND RAY COMING FROM TOP SURFACE ON L.H.S.
                                             !SO TRY COLLECTOR AND SET PARAMETER  D TO ZERO. TEST COMPLETE.
      IF(B**2.LT.4*A*C)  GO TO  44           !NO INTERCEPT ON L.H.S. SO TRY R.H.S.  (RIGHT HAND SIDE SURFACE).
      CALL QUADRT (A,B,C,X2)                 !SUBROUTINE TO FIND THE LARGEST ROOT OF A QUADRATIC.
      IF((RFFM.LT.0).AND.(J.GE.3)) CALL QUADNG(A,B,C,X2)!WITH AN INTERCEPTION ON THE L.H.S. AND RAY -VE FIND THE LEAST ROOT.
                                                !IF SLOPE IS -VE AND INTERCEPT IS NOT ON R.H.S. FIOND SMALLEST ROOT.
      IF((X2.LT.-X).AND.(D.EQ.1))  THEN         !RAY INTERCEPT WITH L.H.S. OUTSIDE BOUNDARY CONDITIONS.
            D=0                                 !D=0 MEANS SIDE SURFACES HAVE BEEN TESTED FOR INTERCEPTION OF RAY.
                                                !PRIOR TO IT BEING TESTED AT THE COLLECTOR.
            GO TO 19                            !THE RAY CAN NOW BE TESTED FOR INTERCEPT WITH COLLECTOR.
      ENDIF
      IF(X2.LT.-X)  THEN                        !INTERCEPT WITH L.H.S. OUTSIDE BOUNDARY CONDITIONS. TRY R.H.S.S.
            X2=X1                               !REPLACE NEW COORDINATE WITH OLD VALUE SINCE IT IS NOT VALID.
            GO TO 44                            !INTERCECPT WITH L.H.S. OUTSIDE BOUNDARY CONDITION .TRY R.H.S.S.
      ENDIF
      J=1                                       !RAY HAS LIGITIMATE INTERCEPTION WITH L.H.S.
      D=0                                       !DO NOT TEST SIDE SURFACES BEFORE THE COLLECTOR. OR TEST COMPLETED.
      GO TO  66                                 !FIND Y COORDINATE  AND UP DATE RESULTS THEN FIND NEXT REFLECTION.
********************************                !SO TEST THE COLLECTOR FOR NEXT INTERCEPTION THEN R.H.S AND L.H.S.
*     RAY FROM TOP SURFACE     *
********************************
21    IF(X1.LT.0)  GO TO  9                     !IF THE RAY IS COMING FROM THE L.H.S.TOP SURFACE  THEN TEST
                                                !INTERCEPT WITH L.H.S. SURFACE BEFORE R.H.S. SURFACE.
44    IF((RAY.GE.90).AND.(RAY.LE.180))  GO TO  88   !IF 90<RAY<180 THEN RAY CAN NOT POSSIBLY INTERCEPT WITH R.H.S.
                                                !THEREFORE TEST INTERCEPT WITH TOP SURFACE.
      IF(J.EQ.2)  GO TO  88                     !RAY COMING FROM R.H.S.  TEST NEXT INTERCEPTIWITH WITH TOP SURFACE.
********************************
*     INTERCEPT R.H.S.         *
********************************
      A=1+RFFM**2                               !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
      B=2*RFFM*RFFC+2*(G-S)                     !THE R.H.S.   (RIGHT HAND SIDE SURFACE).
      C=RFFC**2-S*(2*G-S)
      IF((B**2.LT.4*A*C).AND.(D.EQ.1))  GO TO  19   !TEST SHOWS THAT WHEN RAY IS COMING FROM THE RIGHT HAND TOP SURFACE
                                                !THERE IS NO INTERCEPTION WITH THE R.H.S. SURFACE. SO NOW
                                                !TEST INTERCEPTION WITH COLLECTOR AND SET D=0 TO SHOW TEST COMPLETE.
      IF(B**2.LT.4*A*C)  GO TO 88               !NO INTERCEPT WITH R.H.S.  NEXT TEST INTERCEPTION WITH TOP SURFACE.
      CALL QUADRT (A,B,C,X2)                    !INTERCEPTION WITH R.H.S. SO CALCULATE X COORDINATE.
      IF(X2.GT.X1) CALL QUADNG(A,B,C,X2)        !IF RAY IS IN FOURTH QUADRANT THE SMALLEST INTERCEPT IS REQUIRED.
      IF((X2.GT.X).AND.(D.EQ.1))  GO TO  19     !INTERCEPT OUTSIDE THE SHAPE .TEST COMPLETE. NEXT TEST COLLECTOR.
      IF(X2.GT.X)  GO TO  88                    !INTERCEPT OUTSIDE THE SHAPE. SO NEXT TEST TOP SURFACE.
      J=2                                       !RAY HAS LIGITIMATE INTERCEPTION WITH R.H.S.
      D=0                                       !DO NOT TEST SIDE SURFACES BEFORE THE COLLECTOR; OR TEST COMPLETED.

***********************************************
*     FIND THE Y COORD. EITHER L. OR R.       *
***********************************************

66    IF(J.EQ.1)  THEN                          !FIND Y COORDINATE FOR THE L.H.S. SURFACE INTERCEPT.
93          Y2=DSQRT(S**2+2*(G-S)*S+2*(G-S)*X2-X2**2)   !THE Y COORDINATE FOR THE L.H.S. SURFACE INTERCEPT.
      ELSE
            Y2=DSQRT(S*(2*G-S)-2*(G-S)*X2-X2**2)        !THE Y COORDINATE FOR THE R.H.S. SURFACE INTERCEPT.
      ENDIF
      IF ((J.LE.2).AND.((DABS(X2)-Q).LT.0.0001)) THEN   !TEST TO SEE IF INTERCEPT IS WITHIN THE COLLECTOR.
            Y2=YT                               !FIND THE Y COORDINATE OF THE RAY ON THE COLLECTOR SURFACE.
            X2=(Y2-RFFC)/RFFM                   !FIND THE Y COORDINATE OF THE RAY FOR THIS VALUE OF Y.
            IF(X2.GT.Q)    THEN                 !IF THE NEW X COORDINATE IS OUTSIDE THE COLLECTOR RANGE.
                  X2=Q-0.0001
            ELSE
```

```
                IF (X2.LT.QQ) THEN
                        X2=QQ+0.0001                              !USE ITS LIMITING VALUES.
                ENDIF
        ENDIF
        TRAP=1                                 !TRAP=1 IS THE VARIABLE TO SHOW THE RAY HAS REACHED THE COLLECTOR.
        GO TO  14                              !FIND THE TOTAL LENGTH OF THE RAY IN THE LIQUID BEFORE IT REACHES
      ENDIF                                    !                                                      THE COLLECTOR.
96    REF=REF+1                                !ADD ONE TO THE NUMBER OF SIDE REFLECTIONS.
      RLOP=RLOP+SQRT((X1-X2)**2+(Y1-Y2)**2)
      IF(RLOP.GT.P)  GO TO 450                 !IF RAY IS TOO LONG ITS BEEN MOSTLY ABSORBED SO NEGLECT REMAINDER.
      IF((X2.GT.XZ).OR.(X2.LT.-XZ))  GO TO  450   !IF RAY PASSES OUTSIDE THESE LIMITS ASSUME RAY HAS ESCAPED.
      IF(X2.LT.0)  THEN
        XX=Y2/(X2-(G-S))                       !FIND THE NORMAL OF THE L.H.S. SURFACE AT THE POINT OF INTERCEPTION.
      ELSE
        XX=Y2/(X2-(S-G))                       !FIND THE NORMAL OF THE R.H.S. SURFACE AT THE POINT OF INTERCEPTION.
      ENDIF
      FSNQ=DATAN(XX)                           !THE NORMAL TO THE SIDE SURFACE IN RADIANS ANTICLOCKWISE FROM X AXIS
      FSNQ=FSNQ*180/3.141592653589793238       !THE NORMAL TO THE SIDE SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS
      IF((FSNQ.LT.180).AND.(FSNQ.GT.0))  GO TO  4   !IF NORMAL IN CORRECT QUADRANTS FIND THE REFLECTED RAY.
      FSNQ=FSNQ+180                            !CORRECT THE NORMAL FOR INCORRECT QUADRANTS.
4     IF(J.EQ.2)  THEN                         !IF THE INTERCEPT IS ON THE R.H.S. SURFACE FIND ITS REFLECTED RAY.
        CALL  RAYJ2(RAY,FSNQ,TT)               !FIND THE REFLECTED RAY ANGLE FOR R.H.S SURFACE AND SET TT.
      ELSE
        CALL  RAYJ1(RAY,FSNQ,TT)               !FIND REFLECTED RAY ANGLE FOR L.H.S. SURFACE AND SET PARAMETER TT.
      ENDIF                                    !SET THE DIRECTION PARAMETER TT=1 FOR ALL RAY TRAVELLING UPWARDS.
      X1=X2                                    !THE FINAL COORDINATES OF THE OLD RAY BECOME THE START COORDINATES
      Y1=Y2                                    !OF THE NEW RAY.
      GO TO  33                                !FIND THE SLOPE OF THE NEW RAY AND FIND THE NEXT INTERCEPT.
25    X1=X2                                    !THE FINAL COORDINATES OF THE OLD RAY BECOMES THE INITIAL
      Y1=Y2                                    !COORDINATES OF THE NEW RAY.
      RAYR=RAY*3.141592653589793238/180
      RFFM=DSIN(RAYR)/DCOS(RAYR)               !FIND THE SLOPE OF THE RAY  (RFFM).
      RFFC=Y1-X1*DSIN(RAYR)/DCOS(RAYR)         !FIND THE INTERCEPT OF THE RAY  (RFFC).

****************************************
*     INTERCEPT WITH TOP SURFACE       *
****************************************

88    A=1+RFFM**2                              !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
      B=2*F*RFFM+2*RFFM*RFFC                   !THE TOP SURFACE.
      C=RFFC**2-H**2-2*F*H+2*F*RFFC
      IF(RFFM.LT.0) THEN                       !IF THE SLOPE OF THE RAY IS -VE THEN THE SMALLEST ROOT IS REQUIRED.
        CALL QUADNG (A,B,C,X2)                 !IF SLOPE OF RAY IS -VE THEN THE SMALLEST ROOT IS REQUIRED.
        IF((J.GE.3).AND.(DABS(X2-X1).LE.0.0001))  CALL QUADRT(A,B,C,X2) !POSSIBLE EXCEPTIONS WHEN LARGEST ROOT IS REQUIRED.
      ELSE                                     !SUBROUTINE TO FIND THE LARGEST ROOT OF A QUADRATIC EQUATION.
        CALL QUADRT (A,B,C,X2)
        IF((J.GE.3).AND.(DABS(X2-X1).LE.0.0001))  CALL QUADNG(A,B,C,X2) !IF RAY STARTS ON THE TOP SURFACE MAKE SURE THE
                                               !START COORDINATES ARE NOT THE SAME AS THE FINISH.
      ENDIF
      IF((X2.GT.X).OR.(X2.LT.(-X)))  GO TO  33    !IF INTERCEPT NOT WITHIN THE SHAPE THEN TRY A SIDE SURFACE.
12    A=1                                      !THE PARAMETERS OF THE QUADRATIC EQUATION TO FIND THE Y COORDINATE
      B=2*F                                    !OF THE INTERCEPT WITH THE TOP SURFACE.
      C=X2**2-H**2-2*F*H
      CALL  QUADRT (A,B,C,Y2)                  !SUBROUTINE TO FIND THE LARGEST VALUE OF A QUADRATIC EQUATION.
      IF(X2.GT.XZ.OR.X2.LT.-XZ) GO TO 14       !IF RAY PASSES OUTSIDE THESE THESE LIMITS ASSUME RAY HAS ESCAPED.
      IF(Y2.LT.Y)  GO TO  33                   !IF NEW INTERCEPT IS OUTSIDE THE SHAPE THEN TRY A SIDE SURFACE.
      IF(DABS(Y2-RFFM*X2-RFFC).GE.0.1) GO TO 33   !A TEST TO MAKE SURE THE COORDINATE FOUND ARE OF A POINT ON THE RAY.
      FNQ=DATAN((Y2+F)/X2)                     !FIND THE NORMAL OF THE TOP SURFACE AT THE POINT OF INTERCEPTION.
      FNQ=FNQ*180/3.141592653589793238         !THE NORMAL TO THE TOP SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS.
      IF(FNQ.LT.0)  FNQ=FNQ+180                !MAKE THE NORMAL TO THE TOP SURFACE LIE IN THE 1ST OR 2ND QUADRANTS.
      RR=DABS(RAY-FNQ)                         !THE REFLECTED RAY IS EQUAL TO THE INCIDENCE RAY.
      IF(RR.GT.180)  RR=360-RR                 !THE REFLECTED RAYS ANGLE MUST BE ACUTE.
      IF(RR.LT.40)  GO TO 63                   !IF THE INCIDENCE ANGLE IS<40' THEN RAY IS NOT INTERNALLY REFLECTED.
      J=3
      D=1
      TIR=TIR+1
      RLOP=RLOP+80.6-(9.8*0.434294*ALOG(RLOP*10))/100
      IF(RLOP.GT.P)  GO TO 450
      ANSWER(L,4)=( ANSWER(L,4)+1)
      IF((RAY.GT.FNQ).AND.(RAY.LT.270))  THEN
```

```
          RAY=FNQ-RR+180                                      !THE ANGLE OF TOTALLY INTERNALLY REFLECTED RAY ON THE TOP SURFACE.
      ELSE
          RAY=FNQ+RR+180
      ENDIF
      IF(RAY.GE.360)  RAY=RAY-360                             !CORRECT THE RAY TO BE IN BETWEEN 0' AND 360'.
      IF (RAY. LE.180.AND.RAY.GE.0) THEN
          TT=1
      ELSE
          TT=0
      ENDIF
      GO TO  25

*********************************
*     RAY HAS ESCAPED           *
*********************************

63    TRR=RR
14    RLOP=RLOP+SQRT((X1-X2)**2+(Y1-Y2)**2)          !INTERCEPT TOP OR BOTTOM.
      IF( RLOP.GT.P) GO TO 450
      IF(TRR.LT.40)  GO TO  450
      IF(TRAP.EQ.0)  GO TO  450

*****************************************
*     RAY REACHES RECEIVER PLATE        *
*****************************************

      ANSWER(L,6)=ANSWER(L,6)+((84.6-9.8*LOG10(RLOP))/100)    !FRACTION OF ENERGY REACHING COLLECTOR AT THIS ANGLE
      ANSWER(L,7)=ANSWER(L,7)+1                               !NO OF RAYS REACHING THE COLLECTOR AT THIS ANGLE.
450   ANSWER(L,2)=ANSWER(L,2)+1                               ! COUNTS NUMBER OF RAYS INCIDENT ON TOP SURFACE.
      ANSWER(L,3)=ANSWER(L,3)+REF                    ! COUNTS TOTAL NUMBER OF SIDE REFLECTIONS FOR EACH INCIDENCE ANGLE.
455   CONTINUE
      ANSWER(L,5)=ANSWER(L,6)/ANSWER(L,2)            !FRACTION OF INCIDENT ENERGY REACHING THE COLLECTOR AT THIS ANGLE.
      ANSWER(L,8)=ANSWER(L,7)/ANSWER(L,2)            !FRACTION OF INCIDENT RAYS REACHING THE COLLECTOR AT THIS ANGLE
300   CONTINUE
      CALL EFFY (ANSWER,R1,R2,FF,GG,X,YT,H,ZQ,VOL)
310           CONTINUE
600           CONTINUE
700           CONTINUE
200           CONTINUE
100           CONTINUE
              GO TO  20
50            FORMAT (5X'LENGTH OF RADIUS OF TOP SURFACE',5X,F8.0)
51            FORMAT (5X'LENGTH OF RADIUS OF SIDE SURFACE',4X,F8.0)
52            FORMAT(5X'COORDINATES OF CURVED SURFACE INTERSECTION')
53            FORMAT(5X'( ',F6.2,' , ',F6.2,' )')
'             FORMAT('+'30X,'( ',F6.2,' , ',F6.2,' )')
56            FORMAT(5X'ANGLE OF RAY_____________________________I.Q.')
57            FORMAT(5X'X COORDINATE OF INCOMING RAY-------------C.O.R.')
58            FORMAT(5X'NUMBER OF SIDE REFLECTIONS-------------N.O.S.R.')
59            FORMAT(5X'NUMBER OF TIMES BEAM TOTALLY INTERNALLY ')
69            FORMAT(5X,'REFLECTED ON  TOP SURFACE_____________T.I.R.')
60            FORMAT(5X'INTENSITY AS A PERCENTAGE O F INCIDENT RAYS')
70            FORMAT('+'48X,' INTENSITY.')
61            FORMAT('-',' I.Q.'5X'C.O.R.'5X'N.O.S.R.')
71            FORMAT('+'35X'T.I.R.'5X'RAY.ESC.'5X'INTENSITY.')
62            FORMAT(5X,/,8F10.3,/)
64            FORMAT('+'45X'ESCAPED.')
67            FORMAT('+'22X,F5.1)
68            FORMAT('+'65X,'TO LONG.')
72            FORMAT('+'45X,'COORDINATE IS IN SHADOW.')
73            FORMAT('+'32X,F6.1)
74            FORMAT('+'65X,F6.2)
75            FORMAT('0',' X  COORDINATES OF THE SOLAR TRAP')
76            FORMAT('+'35X,'ARE BETWEEN',F4.1,'  AND',F4.1)
78            FORMAT('-',' THE CENTRE OF THE  TOP CURVED ')
79            FORMAT('+'31X,'SURFACE IS ( 0 ,',F7.1,').')
80            FORMAT(' THE CENTRE OF THE SIDE CURVED SURFACE ARE ')
81            FORMAT('+'43X,'(',F5.1,' , 0 ) AND (',F5.1,' , 0 )')
82            FORMAT(25X,9F10.3)
85            FORMAT(5X' ENERGY ABSORBED AS A ')
86            FORMAT('+'25X,' PERCENTAGE OF INCOMING ENERGY ',4X,F5.2)
20            END
```

```
*
*PROGRAM:      QUADRT.FOR
*WRITTEN BY:   R.W.ELLIOTT.

      SUBROUTINE QUADRT (A,B,C,RT)              !TITLE OF SUBROUTINE WITH EXTERNAL VARIABLES FROM MAIN PROGRAM.
      DOUBLE PRECISION  A,B,C,RT,DIS,DSQRT      !THESE VARIABLES USE VERY HIGH ACCURACY SO AS TO OVERCOME THE
                                                !PROBLEM OF RAYS WHICH PASS NEAR BOUNDARIES OR BOUNDARY INTERCEPTS.
      DIS=B**2-4*A*C                            !FIND THE SQUARE ROOT OF THE DISCRIMINANT OF THE QUADRATIC EQUATION.
      RT=(-B+DSQRT(B**2-4*A*C))/(2*A)           !FIND THE SQUARE ROOT OF THE QUADRATIC EQUATION.
      RETURN                                    !RETURN TO MAIN PROGRAM.
      END                                       !PHYSICAL END OF PROGRAM.
```

```
*
*PROGRAM:       QUADNG.FOR
*WRITTEN BY:    R.W.ELLIOTT.

                SUBROUTINE QUADNG (A,B,C,RT)              !TITLE OF SUBROUTINE WITH EXTERNAL VARIABLES FROM MAIN PROGRAM.
                DOUBLE PRECISION  A,B,C,RT,DSQRT          !THESE VARIABLES USE VERY HIGH ACCURACY SO AS TO OVERCOME THE
                                                          !PROBLEM OF RAYS WHICH PASS NEAR BOUNDARIES OR BOUNDARY INTERCEPTS.
                RT=(-B-DSQRT(B**2-4*A*C))/(2*A)           !FIND THE SQUARE ROOT OF THE QUADRATIC EQUATION.
                RETURN                                    !RETURN TO MAIN PROGRAM.
                END                                       !PHYSICAL END OF PROGRAM.
```

```
*PROGRAM      :RAYJ1.FOR
*WRITTEN BY   :R.W.ELLIOTT.

                                                  !PROGRAM TO FIND THE ANGLE OF THE REFLECTED RAY ON THE L.H.S.S.
      SUBROUTINE  RAYJ1(RAY,FSNQ,TT)              !TITLE OF SUBROUTINE WITH EXTERNAL VARIABLES FROM MAIN PROGRAM.
      DOUBLE PRECISION  RAY,FSNQ                  !THESE VARIABLES USE VERY HIGH ACCURACY SO AS TO OVERCOME THE
      INTEGER*4 TT                                !PROBLEM OF RAYS WHICH PASS NEAR BOUNDARIES OR BOUNDARY INTERCEPTS.
      RAY=2*FSNQ-RAY+180                          !CALCULATE THE ANGLE OF THE REFLECTED RAY.
      IF(RAY.LT.0)  RAY=RAY+360                   !CORRECT THE RAY SO AS TO BE BETWEEN 0' AND 360'.
      TT=1                                        !IF THE RAY IS TRAVELLING UPWARDS THEN PUT TT=1.
      IF(RAY.GT.180)  TT=0                        !IF THE RAY IS TRAVELLING DOWNWARDS THEN PUT TT=0.
      RETURN                                      !RETURN TO MAIN PROGRAM.
      END                                         !PHYSICAL END OF PROGRAM.
```

```
*       PROGRAM:        RAYJ2.FOR
*       WRITTEN BY:     R.W.ELLIOTT.

                                                        !PROGRAM TO FIND THE ANGLE OF THE REFLECTED RAY ON THE R.H.S.S.
        SUBROUTINE  RAYJ2(RAY,FSNQ,TT)                  !TITLE OF SUBROUTINE WITH EXTERNAL VARIABLES FROM MAIN PROGRAM.
        DOUBLE PRECISION  RAY,FSNQ,RAY1                 !THESE VARIABLES USE VERY HIGH ACCURACY SO AS TO OVERCOME THE
        INTEGER*4 TT                                    !PROBLEM OF RAYS WHICH PASS NEAR BOUNDARIES OR BOUNDARY INTERCEPTS.
        RAY1=RAY                                        !RAY1 IS A VARIABLE TO HOLD THE ORIGINAL VALUE OF THE INCIDENT RAY.
        RAY=2*FSNQ-RAY+180                              !CALCULATE THE ANGLE OF THE REFLECTED RAY.
        IF(RAY1.LT.90)  RAY=2*FSNQ-RAY1-180             !CALCULATE SPECIAL CASE ANGLE OF THE REFLECTED RAY.
        IF(RAY.LT.0)  RAY=RAY+180                       !CORRECT THE RAY SO AS TO BE BETWEEN 0' AND 360'.
        TT=1                                            !IF THE RAY IS TRAVELLING UPWARDS THEN PUT TT=1.
        IF(RAY.GT.180)  TT=0                            !IF THE RAY IS TRAVELLING DOWNWARDS THEN PUT TT=0.
        RETURN                                          !RETURN TO MAIN PROGRAM.
        END                                             !PHYSICAL END OF PROGRAM.
```

```
*
*PROGRAM      :EFFY.FOR
*WRITTEN BY   :R.W.ELLIOTT.

        SUBROUTINE    EFFY    (ANS,R1,R2,FF,GG,X,YT,H,Z,VOL)  !THESE VARIABLES HAVE BEEN TRANSFERED FROM THE MAIN PROGRAM.
        DIMENSION  ANSQ(13,2)  ,C(5)  ,RESULT(4,13),  ANS(13,8) !SPECIFY THE DIMENSIONS OF THE ARRAYS USED IN THIS PROGRAM.
                                                                !THESE PARAMETERS ARE VALUES OF K'=K^T/E FOR APPROPRIATE
                                                                !WINTER AND SUMMER CONDITIONS.
                                                      !          TEMP. DIFFERENCE.    ENERGY INCIDENT.
                                                      !SEASON.          ^T'C          E (WM-2S-1.)   K' (M).
        C(1)=0.04                                     !WINTER.           40            100          0.04
        C(2)=0.0067                                   !SUMMER.           40            600          0.0067
        C(3)=0.08                                     !WINTER.           80            100          0.08
        C(4)=0.013                                    !SUMMER.           80            600          0.013
        DO  100  L=1,13                               !A LOOP TO CONSIDER EACH INCIDENT RAY ANGLE FROM 0-30 DEGREES TO THE
                                                      !VERTICAL IN STEPS OF 5'.
        DO  200  KK=1,4                               !A LOOP TO CONSIDER DIFFERENT OPERATING CONDITIONS FOR EACH
                                                      !COLLECTOR SHAPE AND FOR EACH INCIDENT ANGLE.
        A=0.1*Z/(0.02*X*(H-YT))                       !KQ IS A FUNCTION OF THE HEAT LOSS. KQ INCREASES WITH THE HEAT LOSS.
        B=(2*X)/(VOL*0.01)                            !L/V= THE RATIO OF THE WIDTH OF THE COLLECTOR TO ITS VOLUME PER (M).
        RESULT(KK,L)=ANS(L,5)-C(KK)*Z/(0.02*X*(H-YT)) !THE COLLECTOR EFFICIENCY FOR EACH SET OF CONDITIONS AND EACH ANGLE.
        RESULT(KK,L)=RESULT(KK,L)*100                 !THE COLLECTOR EFFICIENCY AS A PERCENTAGE.
        ANSQ(L,1)=ANS(L,8)*100                        !PERCENTAGE OF RAYS REACHING THE COLLECTOR.
        ANSQ(L,2)=ANS(L,5)*100                        !PERCENTAGE OF ENERGY REACHING THE COLLECTOR.
200     CONTINUE                                      !RETURN TO LOOP FOR DIFFERENT OPERATING CONDITIONS.
100     CONTINUE                                      !RETURN TO LOOP TO CONSIDER NEW INCIDENT RAY.
        WRITE(92,2)
        WRITE(92,1)
        WRITE(92,30)
        WRITE(92,3)
        WRITE(92,35)GG
        WRITE(92,4)R1,FF,R2
        WRITE(92,10)(ANSQ(LL,1),LL=1,13)
        WRITE(92,11)
        WRITE(92,10)(ANSQ(LL,2),LL=1,13)
        WRITE(92,9)
        WRITE(92,10)(RESULT(1,LL),LL=1,13)
        WRITE(92,5)
        WRITE(92,10),(RESULT(2,LL),LL=1,13)
        WRITE(92,6)B
        WRITE(92,10)(RESULT(3,LL),LL=1,13)
        WRITE(92,7)
        WRITE(92,10)(RESULT(4,LL),LL=1,13)
        WRITE(92,8)A
1       FORMAT('+','   ROTS.    COTS.    ROSS.  COLSS.')
2       FORMAT(58X,' .ANGLE OF INCIDENT RAY TO THE VERTICAL.')
30      FORMAT(80X,'5     10    15    20    25    30')
3       FORMAT('+',33X,'    30    25    20    15    10    5     0')
35      FORMAT('+',26X,F6.0,',0)')
4       FORMAT('+',F6.0,'CMS(0,',F7.0,')',F4.0,'CMS(')
5       FORMAT('+','              40'C     WINTER.')
6       FORMAT('+',' L/V=',F5.1,'  40'C     SUMMER.')
7       FORMAT('+','              80'C     WINTER.')
8       FORMAT('+',' KQ=',F4.3,'   80'C     SUMMER.')
9       FORMAT('+','% OF ENERGY REACHING THE COLLECTOR')
10      FORMAT(36X,13F6.1)
11      FORMAT('+','% OF   RAYS REACHING THE COLLECTOR')
        RETURN                                         !RETURN TO MAIN PROGRAM.
        END                                            !PHYSICAL END OF PROGRAM.
```

```
*PROGRAM        :VOLUME.FOR
*WRITTEN BY     :R.W.ELLIOTT.

        SUBROUTINE  VOLUME  (R1,R2,X,Y,Q,YT,F,S,VOL)    !SUBROUTINE TO OBTAIN THE VOLUME OF THE SOLAR COLLECTOR.
                                                        !THESE VARIABLES HAVE BEEN TRANSFERED FROM THE MAIN PROGRAM.
        AREA1=X*SQRT(R1**2-X**2)+R1**2*ASIN(X/R1)-2*X*(F+YT)    !AREA1 IS THE AREA UNDER THE TOP ARC AND ABOVE THE COLLECTOR
                                                        !LEVEL AND BOUNDED BY THE X COORDINATES OF THE INTERCEPT OF THE
                                                        !TOP AND SIDE SURFACES OF THE COLLECTOR.
        X1=S+R2-Q                                       !THE UPPER LIMIT OF THE INTEGRAL FOR THE AREA UNDER THE S. SURFACES.
        PLUS=X1*SQRT(R2**2-X1**2)+R2**2*ASIN(X1/R2)     !PLUS IS THE UPPER LIMIT CASE OF THE DEFINITE INTEGRAL TO FIND THE
                                                        !AREA UNDER THE SIDE SURFACE ARCS.
        X1=S+R2-X                                       !THE LOWER LIMIT OF THE INTEGRAL FOR THE AREA UNDER THE S. SURFACES.
        SUB=X1*SQRT(R2**2-X1**2)+R2**2*ASIN(X1/R2)      !SUB IS THE LOWER LIMIT CASE OF THE DEFINITE INTEGRAL TO FIND THE
                                                        !AREA UNDER THE SIDE SURFACE ARCS.
        AREA2=PLUS-SUB-2*YT*(X-Q)                       !AREA2 IS TWICE THE AREA OF THE SECTOR WHOSE AREA IS UNDER THE CURVE
                                                        !OF THE SIDE SURFACE AND BOUNDED BY THE X AXIS AND THE X COORDINATE
                                                        !OF THE TOP AND SIDE SURFACES AND THE X COORDINATE OF THE COLLECTOR.
        VOL=(AREA1-AREA2)                               !VOL= THE VOLUME OF MATERIAL USED INSIDE THE SHAPE PER UNIT LENGTH.
        TYPE 1
        TYPE 2,VOL
1       FORMAT(' THE VOLUME OF COLLECTOR PER UNIT LENGTH IS')
2       FORMAT('+'46X,F6.2,'X10^-4 M^3')
        RETURN                                          !RETURN TO MAIN PROGRAM.
        END                                             !PHYSICAL END TO PROGRAM.
```

APPENDIX B

```
*
*PROGRAM       :RWE92.FOR
*WRITTEN BY    :R.W.ELLIOTT.

      DOUBLE PRECISION  A,B,C,G,F,X,Y,X1,X2,Y1,Y2,YT,XI,XX,CK,Z          !THESE VARIABLES USE VERY HIGH ACCURACY SO AS TO
      DOUBLE PRECISION  DIS,R2,RT,RI,RR,RAY,FNQ,FSNQ,RFFM,RFFC           !OVERCOME THE PROBLEM OF RAYS WHICH PASS NEAR
      DOUBLE PRECISION  COSD,ASIN,SIND,DATAN,DSQRT,DABS,RAYR,DSIN,DCOS           !BOUNDARIES OR BOUNDARY INTERCEPTS.
      integer*4       TT,D
      DIMENSION ANSWER(13,8),TABLE(18,15)                  !CREATE TWO 2 DIMENSIONAL ARRAYS  WHICH ARE 13X8 AND 18X15.

      OPEN(UNIT=92,NAME='RWE92.DAT',TYPE='NEW')

      U=1.526                                                  !THE REFRACTIVE INDEX OF THE 'HYVIS 2000'.
      N=1
      S=0                                              !S IS A PARAMETER FOR LATERAL MOVEMENT OF THE SIDE SURFACES.
      L=0                                              !L IS A PARAMETER FOR CHANGING THE ANGLE OF THE LIGHT RAYS.
      P=1000000                                        !ANY RAY LONGER THAN 10 METERS IS IGNORED (HARDLY ANY).
      DO 100 IT=9,9                                    !A LOOP TO CHANGE THE RADIOUS OF THE TOP SURFACE.
      R1=5*2**IT-10                                    ! -F IS THE CENTRE OF THE TOP SURFACE.
                                                       !R1 IS THE RADIOUS OF THE TOP SURFACE.
      DO 200 IS=4,4                                    !A LOOP TO CHANGE THE RADIOUS OF THE SIDE REFLECTING SURFACE
      G=6-4*2**IS                                      !G IS A PARAMETER FOR THE SIDE REFLECTING SURFACES.
      DO 700 IH=15,15                                  !A LOOP TO REDUCE THE HEIGTH, WITHOUT CHANGING THE RADIOUS.
      H=IH                                             !THE Y AXIS INTERCEPT OF THE TOP SURFACE.
      F=R1-H                                           !ADJUSTMENT OF F WHEN TOP SURFACE IS LOWERED.
      FF=(-F)                                          !THE Y COORDINATE OF THE CENTRE OF THE TOP SURFACE.
      DO  600  S=1,1                                   !A LOOP TO MOVE OUT THE SIDES WITHOUT CHANGING THE RADIOUS.
                                                       !PARAMETER FOR CHANGING THE SIDES CENTRE WITH SAME RADIOUS.
      R2=DABS(G)                                       ! R2 IS THE RADIOUS OF THE SIDE SURFACES.
      GG=R2+S                                          ! X COORDINATES OF THE CENTRES OF THE TWO SIDE REFLECTING
      GGG=(-GG)                                        ! SURFACES.
      IF(DABS(F).LE.0.0001)  GO TO  700                !IF THE CENTRE OF THE TOP IS ON X AXIS EQUATIONS ARE UNTRUE.
      CK=(H**2+2*F*H-S*(2*G-S))/(2*F)                  !THE CONSTANTS IN THE QUADRATIC EQUATION THAT WILL EVALUATE
      A=1+(G-S)**2/F**2                                !THE INTERCEPT BETWEEN THE SIDE SURFACES AND THE TOP SURFACE
      B=2*(G-S)*(CK+F)/F
      C=CK**2+2*F*CK-H**2-2*F*H
      IF(B**2-4*A*C)200,2,2                            !IF THE DISCRIMINANT IS NEGATIVE THEN NO INTERCEPT.
2     CALL QUADRT ( A,B,C,X)                           !SUBROUTINE TO EVALUATE A QUADRATIC ; AND GIVE +VE ROOT.
      IF(F.GT.0)  X=(-B-DSQRT(B**2-4*A*C))/(2*A)       !IF CENTRE OF TOP SURFACE IS NEGATIVE WE NEED OTHER ROOT.
      Y=(G-S)*X/F+CK                                   ! Y COORDINATE OF THIS INTERCEPT.
      IXQ=X/2                                          !CONDITION THAT CONCENTRATION IS > A FACTOR OF TWO.
      IF(IXQ.LT.S)  GO TO 700                          !IF SIDES ARE TO FAR APART CHANGE THE SHAPE.
      WRITE(92,78)                                     !PRINT OUT OF THE REFERENCES AND COORDINATES OF THIS SHAPE
      WRITE(92,79) FF                                  !IE. THE CENTRES, RADII AND INTERCEPTS.
      WRITE(92,80)
      WRITE(92,81)GGG,GG
      WRITE(92,50)R1
      WRITE(92,51)R2
      WRITE(92,52)
      X=(-X)
      WRITE(92,53) X , Y
      X=(-X)
      WRITE(92,54) X , Y
      WRITE(92,56)
      WRITE(92,57)
      WRITE(92,58)
      WRITE(92,59)
      WRITE(92,69)
      WRITE(92,60)
      WRITE(92,70)                                     !THIS LOOP DETERMINES THE WIDTH OF THE COLLECTOR PLATE.
      DO 310 IQ=1,IXQ,1                                !Q IS THE RIGHT HAND X COORDINATE OF THE COLLECTOR PLATE.
      Q=IQ                                             !TEST IF COLLECTOR WIDTH IS < DISTANCE BETWEEN SIDES.
      IF(Q.LT.S)  GO TO  310                           ! QQ IS THE LEFT HAND X COORDINATE OF THE COLLECTOR.
      QQ=(-Q)
      YT=(S*(2*G-S)-2*(G-S)*Q-Q**2)                    !THE Y COORDINATE OF THE COLLECTOR PLATE.
      YT=DSQRT(YT)
```

```
      ZQ=Q-QQ                                  ! ZQ IS THE WIDTH OF THE COLLECTOR.
      WRITE(92,75)                             !PRINT THE REFERENCES FOR THE COLLECTOR.
      WRITE(92,76)Q,QQ
      CALL VOLUME (R1,R2,X,Y,Q,YT,F,S,VOL)     !SUBROUTINE TO OBTAIN THE INTERNAL VOLUME OF THE COLLECTOR.
      L=0                                      !L IS A PARAMETER FOR THE DIFFERENT INCIDENCE RAYS.
      DO 300 LQ=240,300,5                      ! TO CHANGE THE ANGLE AT WHICH THE RAYS ENTER THE COLLECTOR.
      WRITE(92,82)LQ
      WRITE(92,61)
      WRITE(92,71)
      WRITE(92,87)
      REF=0                                    !REF IS THE NUMBER OF REFLECTIONS. AT START SET TO ZERO.
      IX=99*X                                  !RANGE OF INCIDENCE RAYS ON THE TOP SURFACE MAGNIFIED BY 99.
      XZ=0.9999*X                              !CONDITION : COORDINATE FOR LIMIT OF  BOUNDARY ACCURACY.
      L=L+1                                    !FIRST VALUE OF L FOR FIRST CONSIDERED INCIDENCE ANGLE.
      ANSWER(L,1)= LQ                          !ANGLE OF INCIDENCE FOR EACH  VALUE OF L.
      ANSWER(L,2) = 0                          !NUMBER OF RAYS INCIDENT ON TOP SURFACE BEING CONSIDERED.
      ANSWER(L,3) = 0                          !NUMBER OF SIDE REFLECTIONS FOR THIS SHAPE AT THIS ANGLE.
      ANSWER(L,4) = 0                   !NUMBER OF TOTAL INTERNAL REFLECTIONS FOR THIS SHAPE AT THIS ANGLE.
      ANSWER(L,5) = 0                   !THE FRACTION OF INCIDENT ENERGY REACHING COLLECTOR AT THIS ANGLE.
      ANSWER(L,6) = 0                   !NUMBER OF RAYS REACHING THE COLLECTOR AFTER ABSORBTION LOSES.
      ANSWER(L,7) = 0                   !NUMBER OF RAYS INCIDENT REACHING THE COLLECTOR.
      ANSWER(L,8)=0                     !FRACTION OF INCIDENT RAYS REACHING THE COLLECTOR AT THIS ANGLE.
      DO 455 IXI=(-IX),IX               !A LOOP TO CONSIDER EACH RAY, LEAVING 1% OF WIDTH AT BOUNDARIES.
      XI=IXI                            ! X COORDINATE OF INCIDENT RAY MAGNIFIED BY 100 TIMES.
      X1=XI/100                         ! X COORDINATE OF THE INCIDENT RAY. EACH RAY 1/100TH OF A CM APART.
      CALL   VERN    (X1,R1,ANSWER(L,1),V)  !A SUBROUTINE TO FIND THE VERNIER READING EQUIVALENT TO THE
                                        !X COORDINATE OF THE INCOMING RAY.
      WRITE(92,65)V,X1
      TRR=90                            ! PARAMETER FOR TOTALLY INTERNALLY REFLECTED RAY. PRESET TO
                                        ! LARGE VALUE SO AS THIS CONDITION WILL NOT EJECT RAY UNLESS RESET
                                        ! BY TOTAL INTERNAL REFLECTING CONDITION.
      TIR=0                             ! COUNTS THE NUMBER OF TIMES RAY TOTALLY INTERNALLY REFLECTED.
      TRAP=0                            !CONDITION. IF TRAP=0 THEN RAY HAS NOT REACHED THE COLLECTOR.
      RLOP=0.1                                 !ASSUME 5.6% ABSORPTION IN FIRST 1MM. REFLECTION LOSSES TO BE ADDED.
      REF=0                             !RESET NO OF REFLECTIONS TO ZERO FOR NEW RAY.
******************************************
*     RAY STARTING FROM TOP SURFACE   *
******************************************
      J=4                               !IF J=4 THEN RAY IS ENTERING THE TOP SURFACE.
      D=1                               !IF D=1 THEN RAY IS COMING FROM TOP SURFACE AND RAY MUST BE TESTED
                                        !FOR INTERCEPTION ON SIDE SURFACES BEFORE TESTING AT THE COLLECTOR.
      A=1                               !PARAMETERS OF THE EQUATION FOR THE Y VALUE OF THE INCOMING RAY.
      B=2*F
      C=X1**2-H**2-2*F*H
1     CALL QUADRT (A,B,C,Y1)            !Y1 IS THE Y COORDINATE OF THE STARTING POINT OF THE RAY.
      IF(X1.EQ.0) THEN                  !AT THIS POINT THE NORMAL 'FNQ' IS VERTICAL THEREFORE SET FNQ = 90'.
            FNQ=90                      !SET THE NORMAL OF THE TOP SURFACE TO 90'.
      ELSE                              !RETURN TO PROGRAM TO CALCULATE THE REFRACTED RAYS ANGLE  (RAY).
            FNQ=DATAN((Y1+F)/X1)        !THE NORMAL TO THE TOP SURFACE IN RADIANS ANTICLOCKWISE FROM X AXIS.
            FNQ=FNQ*180/3.14159265358979323 8 !THE NORMAL TO THE TOP SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS.
            IF(FNQ.LT.0)  FNQ=FNQ+180
      ENDIF
3     I=LQ-180                          !I IS A PARAMETER FOR THE INCIDENT RAY.
      IF(I.LE.FNQ)  RI=FNQ-I            !RI IS THE ANGLE OF INCIDENCE FOR THE INCOMING RAY.
      IF(I.GT.FNQ)  RI=I-FNQ
      IF(RI.GE.90)  GO TO  390          !IF THE INCIDENCE ANGLE IS GREATER THAN 90' THEN COORDINATE IS IN SHADOW.
      RR=ASIN(SIND(RI)/U)               !REFRACTED ANGLE IN RADIANS.
      RR=RR*180/3.141592653589793238    !REFRACTED ANGLE IN DEGREES.
      IF(I.LE.FNQ)  RAY=FNQ-RR+180      !RAY IS THE ANGLE THE LIGHT BEAM MAKES WITH THE X AXIS.
      IF(I.GT.FNQ)  RAY=FNQ+RR+180
      IF(RAY.EQ.90.OR.RAY.EQ.270)  X2=X1  !IF RAY IS VERTICAL ITS SLOPE IS INFINITE SO PUT X2=X1.
                                        !IF RAY IS VERTICAL PUT X2=X1 AND FIND THE Y INTERCEPT.
      RN=RR-RI                          !THE DIFFERENCE BETWEEN THE INCIDENT AND REFRACTED ANGLES.
      RP=RR+RI                          !THE ADDITION OF THE INCIDENT AND REFRACTED ANGLES.
      IF (RN.LE.0.1) THEN
            R=((U-1)/(U+1))**2
```

```
      ELSE
            R=1/2*(((SIND(RN))**2/(SIND(RP))**2)+((TAND(RN))**2/(TAND(RP))**2))
      ENDIF                                  !THE REFLECTANCE ON THE TOP SURFACE. FRESNELL RELATIONSHIP.
      RLOP=10**((84.6+R*100-94.4)/9.8)       !THE APPARENT LENGTH OF THE RAY DUE TO REFLECTION ON TOP SURFACE.
      IF(RAY.EQ.90)  GO TO  12               !IF RAY+90 ONLY INTERCEPT IS WITH THE TOP SURFACE.
      IF(RAY.EQ.270)  GO TO  17              !IF RAY=270 THEN RAY CAN ONLY BE COMING FROM THE TOP SURFACE.

*********************************
*     RAY STARTING TREK         *
*********************************
33    RAYR=RAY*3.14159265358979323 8/180
      RFFM=DSIN(RAYR)/DCOS(RAYR)             !FIND THE SLOPE OF THE RAY  (RFFM).
      RFFC=Y1-X1*DSIN(RAYR)/DCOS(RAYR)       !FIND THE INTERCEPT OF THE RAY  (RFFC).
      IF(RAY.LT.90.AND.J.EQ.2)  GO TO  88    !IF J=2 THEN RAY IS COMING FROM R.H.S. AND WITH RAY < 90' IT CAN ONLY
                                             !INTERCEPT WITH THE TOP SURFACE.
      IF(TT.EQ.1.AND.D.EQ.0)  GO TO  9       !D=0 MEANS COLLECTOR IS NOT HIDDEN FROM RAY. TT=1 MEANS
                                             !RAY < 180' THEREFORE IMPOSSIBLE INTERCEPT WITH COLLECTOR.
      IF(D.EQ.1)  GO TO  21                  !TEST THE SIDE SURFACES BEFORE THE COLLECTOR FOR RAY INTERSECTION

*****************************************    !BECAUSE RAY IS COMING FROM  THE TOP SURFACE.
*     RAY INTERCEPT WITH COLLECTOR      *
*****************************************

19    X2=(-RFFC/RFFM)                        !X2 IS THE RAY INTERCEPT ON THE X AXIS.
17    IF((DABS(X2)-S).LE.0.0001)  THEN       !THE RAY ENTERS THE COLLECTOR.
            Y2=YT                            !FIND THE Y COORDINATE OF THE RAY ON THE COLLECTOR SURFACE.
            IF(X2.GT.S)     THEN
                  X2=S-0.0001                !IF THE NEW X COORDINATE IS OUTSIDE THE COLLECTOR RANGE.
            ELSE
                  IF (X2.LT.(-S)) THEN
                  X2=0.0001-S                !USE ITS LIMITING VALUES.
                  ENDIF
            ENDIF
            TRAP=1                           !TRAP =1 IS THE VARIABLE TO SHOW THE RAY HAS REACHED THE COLLECTOR.
            GO TO 14                         !NOW FIND THE TOTAL LENGTH OF THE RAY IN THE LIQUID.
      ENDIF
      X2=X1                                  !REPLACE X2 WITH ORIGINAL VALUE SINCE THIS VALUE IS INCORRECT.
      D=0
9     IF(J.EQ.1)  GO TO  44                  !RAY COMING FROM L.H.S. THEREFORE TEST FOR INTERCEPT ON R.H.S.

*********************************
*     INTERCEPT L.H.S.          *
*********************************

      A=1+RFFM**2                            !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
      B=2*RFFM*RFFC-2*(G-S)                  !THE L.H.S.  (LEFT HAND SIDE SURFACE).
      C=RFFC**2-2*(G-S)*S-S**2
      IF(B**2.LT.4*A*C.AND.D.EQ.1)  GO TO  19   !NO INTERCEPT ON L.H.S. AND RAY COMING FROM TOP SURFACE ON L.H.S.
                                             !SO TRY COLLECTOR AND SET PARAMETER  D TO ZERO. TEST COMPLETE.
      IF(B**2.LT.4*A*C)  GO TO  44           !NO INTERCEPT ON L.H.S. SO TRY R.H.S.  (RIGHT HAND SIDE SURFACE).
      CALL QUADRT (A,B,C,X2)                 !SUBROUTINE TO FIND THE LARGEST ROOT OF A QUADRATIC.
      IF(RFFM.LT.0.AND.J.GE.3) CALL QUADNG(A,B,C,X2)  !WITH AN INTERCEPTION ON THE L.H.S. AND RAY -VE FIND THE LEAST ROOT.
                                             !IF SLOPE IS -VE AND INTERCEPT IS NOT ON R.H.S.FIND SMALLEST ROOT.
      IF(X2.LT.-X.AND.D.EQ.1)  THEN          !RAY INTERCEPT WITH L.H.S. OUTSIDE BOUNDARY CONDITIONS.
            D=0                              !D=0 MEANS SIDE SURFACES HAVE BEEN TESTED FOR INTERCEPTION OF RAY
                                             !PRIOR TO IT BEING TESTED AT THE COLLECTOR.
            GO TO  19                        ! THE RAY CAN NOW BE TESTED FOR INTERCEPT WITH THE COLLECTOR.
      ENDIF
      IF(X2.LT.-X)  THEN                     !INTERCEPT WITH L.H.S. OUTSIDE BOUNDARY CONDITIONS. TRY R.H.S.S.
            X2=X1                            !REPLACE NEW COORDINATE WITH OLD VALUE SINCE IT IS NOT VALID.
            GO TO  44                        !INTERCEPT WITH L.H.S. OUTSIDE BOUNDARY CONDITION. TRY R.H.S.S.
      ENDIF
      J=1                                    !RAY HAS LIGITIMATE INTERCEPTION WITH L.H.S.
      D=0                                    !DO NOT TEST SIDE SURFACES BEFORE THE COLLECTOR. OR TEST COMPLETED.
      GO TO  66                              !FIND Y COORDINATE  AND UP DATE RESULTS THEN FIND NEXT REFLECTION.
```

```
********************************                    !SO TEST THE COLLECTOR FOR NEXT INTERCEPTION THEN R.H.S AND L.H.S.
*     RAY FROM TOP SURFACE     *
********************************

21     IF(X1.LT.0)  GO TO  9                         !IF THE RAY IS COMING FROM THE L.H.S.TOP SURFACE  THEN TEST
                                                     !INTE RCEPT WITH L.H.S. SURFACE BEFORE R.H.S. SURFACE.
44     IF(RAY.GE.90.AND.RAY.LE.180)  GO TO  88       !IF 90<RAY<180 THEN RAY CAN NOT POSSIBLY INTERCEPT WITH R.H.S.
                                                     !THEREFORE TEST INTERCEPT WITH TOP SURFACE.
       IF(J.EQ.2)  GO TO  88                         !RAY COMING FROM R.H.S.  TEST NEXT INTERCEPTIWITH WITH TOP SURFACE.

********************************
*     INTERCEPT R.H.S.         *
********************************

       A=1+RFFM**2                                   !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
       B=2*RFFM*RFFC+2*(G-S)                         !THE R.H.S.   (RIGHT HAND SIDE SURFACE).
       C=RFFC**2-S*(2*G-S)
       IF(B**2.LT.4*A*C.AND.D.EQ.1)  GO TO  19       !TEST SHOWS THAT WHEN RAY IS COMING FROM THE RIGHT HAND TOP SURFACE
                                                     !THERE IS NO INTERCEPTION WITH THE R.H.S. SURFACE. SO NOW
                                                     !TEST INTERCEPTION WITH COLLECTOR AND SET D=0 TO SHOW TEST COMPLETE.
       IF(B**2.LT.4*A*C)  GO TO 88                   !NO INTERCEPT WITH R.H.S.  NEXT TEST INTERCEPTION WITH TOP SURFACE.
       CALL QUADRT (A,B,C,X2)                        !INTERCEPTION WITH R.H.S. SO CALCULATE X COORDINATE.
       IF(X2.GT.X1) CALL QUADNG(A,B,C,X2)            !IF RAY IS IN FOURTH QUADRANT THE SMALLEST INTERCEPT IS REQUIRED.
       IF(X2.GT.X.AND.D.EQ.1)  GO TO  19             !INTERCEPT OUTSIDE THE SHAPE .TEST COMPLETE. NEXT TEST COLLECTOR.
       IF(X2.GT.X)  GO TO  88                        !INTERCEPT OUTSIDE THE SHAPE. SO NEXT TEST TOP SURFACE.
       J=2                                           !RAY HAS LIGITIMATE INTERCEPTION WITH R.H.S.
       D=0                                           !DO NOT TEST SIDE SURFACES BEFORE THE COLLECTOR; OR TEST COMPLETED.

*************************************************
*     FIND THE Y COORD. EITHER L. OR R.         *
*************************************************

66     IF(J.EQ.1)  THEN                              !FIND Y COORDINATE FOR THE L.H.S. SURFACE INTERCEPT.
93          Y2=DSQRT(S**2+2*(G-S)*S+2*(G-S)*X2-X2**2)        !THE Y COORDINATE FOR THE L.H.S. SURFACE INTERCEPT.
       ELSE
            Y2=DSQRT(S*(2*G-S)-2*(G-S)*X2-X2**2)             !THE Y COORDINATE FOR THE R.H.S. SURFACE INTERCEPT.
       ENDIF
       IF((J.LE.2).AND.((DABS(X2)-Q).LE.0.0001))  THEN !TEST TO SEE IF INTERCEPT IS WITHIN THE COLLECTOR.
            Y2=YT                                    !FIND THE Y COORDINATE OF THE RAY ON THE COLLECTOR SURFACE.
            X2=(Y2-RFFC)/RFFM                        !FIND THE X COORDINATE OF THE RAY FOR THIS VALUE OF Y.
            IF(X2.GT.Q)  THEN
                 X2=Q-0.0001                         !IF THE NEW X COORDINATE IS OUTSIDE THE COLLECTOR RANGE
            ELSE
                 IF(X2.LT.QQ)  THEN
                      X2=QQ+0.0001                   !USE ITS LIMITING VALUES.
                 ENDIF
            ENDIF
            TRAP=1                                   !TRAP=1 IS THE VARIABLE TO SHOW THE RAY HAS REACHED THE COLLECTOR.
            GO TO  14                                !FIND THE TOTAL LENGTH OF THE RAY IN THE LIQUID BEFORE IT REACHES
       ENDIF
96     REF=REF+1                                     !ADD ONE TO THE NUMBER OF SIDE REFLECTIONS.
       RLOP=RLOP+DSQRT((X1-X2)**2+(Y1-Y2)**2)        !RECORD THE NEW LENGTH OF THE PATH OF THE RAY.
       IF(RLOP.GT.P)  GO TO 410                      !IF RAY IS TOO LONG ITS BEEN MOSTLY ABSORBED SO NEGLECT REMAINDER.
       IF(X2.GT.XZ.OR.X2.LT.-XZ)  GO TO  10          !IF RAY PASSES OUTSIDE THESE LIMITS ASSUME RAY  HAS ESCAPED.
       IF(X2.LT.0)  THEN
            XX=Y2/(X2-(G-S))                         !FIND THE NORMAL OF THE L.H.S. SURFACE AT THE POINT OF INTERCEPTION.
       ELSE
            XX=Y2/(X2-(S-G))                         !FIND THE NORMAL OF THE R.H.S. SURFACE AT THE POINT OF INTERCEPTION.
       ENDIF
       FSNQ=DATAN(XX)                                !THE NORMAL TO THE SIDE SURFACE IN RADIANS ANTICLOCKWISE FROM X AXIS
       FSNQ=FSNQ*180/3.141592653589793238            !THE NORMAL TO THE SIDE SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS
       IF((FSNQ.LT.180).AND.(FSNQ.GT.0))  THEN       !IF NORMAL IN CORRECT QUADRANTS FINDTHE REFLECTED RAY.
            GO TO 4
       ELSE
            FSNQ=FSNQ+180                            !CORRECT THE NORMAL FOR INCORRECT QUADRANTS.
       ENDIF
```

```
4      IF(J.EQ.2)  THEN                               !IF THE INTERCEPT IS ON THE R.H.S. SURFACE FIND ITS REFLECTED RAY.
              CALL  RAYJ2(RAY,FSNQ,TT)                !FIND THE REFLECTED RAY ANGLE FOR R.H.S SURFACE AND SET TT.
       ELSE
              CALL  RAYJ1(RAY,FSNQ,TT)                !FIND REFLECTED RAY ANGLE FOR L.H.S. SURFACE AND SET PARAMETER TT.
       ENDIF
       X1=X2                                          !THE FINAL COORDINATES OF THE OLD RAY BECOME THE START COORDINATES
       Y1=Y2                                          !OF THE NEW RAY.
       GO TO  33                                      !FIND THE SLOPE OF THE NEW RAY AND FIND THE NEXT INTERCEPT.
25     X1=X2                                          !THE FINAL COORDINATES OF THE OLD RAY BECOMES THE INITIAL
       Y1=Y2                                          !COORDINATES OF THE NEW RAY.
       RAYR=RAY*3.14159265358979323238/180
       RFFM=DSIN(RAYR)/DCOS(RAYR)                     !FIND THE SLOPE OF THE RAY  (RFFM).
       RFFC=Y1-X1*DSIN(RAYR)/DCOS(RAYR)               !FIND THE INTERCEPT OF THE RAY  (RFFC).

****************************************
*      INTERCEPT WITH TOP SURFACE      *
****************************************

88     A=1+RFFM**2                                    !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
       B=2*F*RFFM+2*RFFM*RFFC                         !THE TOP SURFACE.
       C=RFFC**2-H**2-2*F*H+2*F*RFFC
       IF(RFFM.LT.0) THEN                             !IF THE SLOPE OF THE RAY IS -VE THEN THE SMALLEST ROOT IS REQUIRED.
              CALL QUADNG(A,B,C,X2)                   !IF SLOPE OF RAY IS -VE THEN THE SMALLEST ROOT IS REQUIRED.
              IF(J.GE.3.AND.DABS(X2-X1).LE.0.0001) CALL QUADRT(A,B,C,X2)      !POSSIBLE EXCEPTIONS WHEN LARGEST ROOT IS REQUIRED.
       ELSE
              CALL QUADRT (A,B,C,X2)                  !SUBROUTINE TO FIND THE LARGEST ROOT OF A QUADRATIC EQUATION.
              IF(J.GE.3.AND.DABS(X2-X1).LE.0.0001)  CALL QUADNG(A,B,C,X2)     !IF RAY STARTS ON THE TOP SURFACE MAKE SURE THE
                                                                              !START COORDINATES ARE NOT THE SAME AS THE FINISH.
       ENDIF
       IF(X2.GT.X.OR.X2.LT.(-X))  GO TO  33           !IF INTERCEPT IS NOT WITHIN THE REQUIRED SHAPE, TRY A SIDE SURFACE.
12     A=1                                            !THE PARAMETERS OF THE QUADRATIC EQUATION TO FIND THE Y COORDINATE
       B=2*F                                          !OF THE INTERCEPT WITH THE TOP SURFACE.
       C=X2**2-H**2-2*F*H
       CALL  QUADRT (A,B,C,Y2)                        !SUBROUTINE TO FIND THE LARGEST VALUE OF A QUADRATIC EQUATION.
       IF(X2.GT.XZ.OR.X2.LT.-XZ)  GO TO  11           !IF RAY PASSES OUTSIDE THESE LIMITS ASSUME RAY HAS ESCAPED.
       IF(Y2.LT.Y)  GO TO  33                         !IF NEW INTERCEPT IS OUTSIDE THE SHAPE THEN TRY A SIDE SURFACE.
       IF(DABS(Y2-RFFM*X2-RFFC).GE.0.1) GO TO 33      !A TEST TO MAKE SURE THE COORDINATE FOUND ARE OF A POINT ON THE RAY.
       FNQ=DATAN((Y2+F)/X2)                           !FIND THE NORMAL OF THE TOP SURFACE AT THE POINT OF INTERCEPTION.
       FNQ=FNQ*180/3.14159265358979323238             !THE NORMAL TO THE TOP SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS.
       IF(FNQ.LT.0)  FNQ=FNQ+180                      !MAKE THE NORMAL TO THE TOP SURFACE LIE IN THE 1ST OR 2ND QUADRANTS.
       RR=DABS(RAY-FNQ)                               !THE REFLECTED RAY IS EQUAL TO THE INCIDENCE RAY.
       IF(RR.GT.180)  RR=360-RR                       !THE REFLECTED RAYS ANGLE MUST BE ACUTE.
       IF(RR.LT.40)  GO TO 63                         !IF THE INCIDENCE ANGLE IS<40' THEN RAY IS NOT INTERNALLY REFLECTED.
       J=3
       D=1
       TIR=TIR+1
       RLOP=RLOP+DSQRT((X1-X2)**2+(Y1-Y2)**2)
       IF(RLOP.GT.P)  GO TO 410
       ANSWER(L,4)=( ANSWER(L,4)+1)
       IF(RAY.GT.FNQ.AND.RAY.LT.270)  THEN
              RAY=FNQ-RR+180                          !THE ANGLE OF TOTALLY INTERNALLY REFLECTED RAY ON THE TOP SURFACE.
       ELSE
              RAY=FNQ+RR+180
       ENDIF
       IF(RAY.GE.360)  RAY=RAY-360                    !CORRECT THE RAY TO BE IN BETWEEN 0' AND 360'.
       IF (RAY.LE.180.AND.RAY.GE.0) THEN
              TT=1
       ELSE
              TT=0
       ENDIF
       GO TO  25                                      !THE COLLECTOR.

************************
*     RAY HAS ESCAPED *
************************
```

```
63    TIR=TIR
11    WRITE(92,64)
14    RLOP=RLOP+DSQRT((X1-X2)**2+(Y1-Y2)**2)
      IF( RLOP.GT.P) GO TO 403
      IF(TIR.LT.40)  GO TO  400
      IF(TRAP.EQ.0)  GO TO  400
      ANSWER(L,6)=ANSWER(L,6)+((80.6-9.8*0.434294*ALOG(RLOP*10))/100)  !FRACTION OF ENERGY REACHING COLLECTOR AT THIS ANGLE
      ANSWER(L,7)=ANSWER(L,7)+1                                         !NO OF RAYS REACHING THE COLLECTOR AT THIS ANGLE.
      WRITE(92,86) X2
      GO TO  400
10    WRITE(92,64)
      GOTO 400
390   WRITE(92,72)
      GO TO 455
410   WRITE(92,68)
400   WRITE(92,74)RLOP
403   WRITE(92,67)REF
      WRITE(92,73)TIR
405   IF(RLOP.LE.P)  GO TO 450
      WRITE(92,68)
450   ANSWER(L,2)=ANSWER(L,2)+1                      ! COUNTS NUMBER OF RAYS INCIDENT ON TOP SURFACE.
      ANSWER(L,3)=ANSWER(L,3)+REF                ! COUNTS TOTAL NUMBER OF SIDE REFLECTIONS FOR EACH INCIDENCE ANGLE.
455   CONTINUE
      ANSWER(L,5)=ANSWER(L,6)/ANSWER(L,2)        !FRACTION OF INCIDENT ENERGY REACHING THE COLLECTOR AT THIS ANGLE.
      ANSWER(L,8)=ANSWER(L,7)/ANSWER(L,2)        !FRACTION OF INCIDENT RAYS REACHING THE COLLECTOR AT THIS ANGLE
      WRITE(92,62) (ANSWER(L,J),J=1,8)
300   CONTINUE
      CALL EFFY (ANSWER,R1,R2,FF,GG,X,YT,H,ZO,VOL)
310   CONTINUE
      GO TO 20
600   CONTINUE
700   CONTINUE
200   CONTINUE
100   CONTINUE
      GO TO  20
50    FORMAT (5X'LENGTH OF RADIUS OF TOP SURFACE',5X,F8.0)
51    FORMAT (5X'LENGTH OF RADIUS OF SIDE SURFACE',4X,F8.0)
52    FORMAT(5X'COORDINATES OF CURVED SURFACE INTERSECTION')
53    FORMAT(5X'( ',F6.2,' , ',F6.2,' )')
54    FORMAT('+',30X,'( ',F6.2,' , ',F6.2,' )')
56    FORMAT(5X'ANGLE OF RAY________________________________LO.')
57    FORMAT(5X'X COORDINATE OF INCOMING RAY______________C.O.R.')
58    FORMAT(5X'NUMBER OF SIDE REFLECTIONS________________N.O.S.R.')
59    FORMAT(5X'NUMBER OF TIMES BEAM TOTALLY INTERNALLY ')
69    FORMAT(5X,'REFLECTED ON  TOP SURFACE ____________________T.I.R.')
60    FORMAT(5X'INTENSITY AS A PERCENTAGE O F INCIDENT RAYS')
70    FORMAT('+',48X,' INTENSITY.')
61    FORMAT(' VERNIER.'5X'C.O.R.'5X'N.O.S.R.')
71    FORMAT('+',38X'T.I.R.'5X'LEN. PATH.'5X'RAY.ESC.  OR')
62    FORMAT(5X,8F10.3)
64    FORMAT('+',65X'ESCAPED.')
65    FORMAT( F8.3,8X,F6.2)
67    FORMAT('+',24X,F5.1)
68    FORMAT('+',65X,'TO LONG.')
72    FORMAT('+',45X,'COORDINATE IS IN SHADOW.')
73    FORMAT('+',36X,F6.1)
74    FORMAT('+',50X,F8.2)
75    FORMAT('0',' X  COORDINATES OF THE SOLAR TRAP')
76    FORMAT('+',35X,'ARE BETWEEN',F4.1,'  AND',F4.1)
78    FORMAT(' THE CENTRE OF THE  TOP CURVED ')
79    FORMAT('+',31X,'SURFACE IS ( 0 ,',F7.1,').')
80    FORMAT(' THE CENTRE OF THE SIDE CURVED SURFACE ARE ')
81    FORMAT('+',43X,'(',F5.1,' , 0 ) AND (',F5.1,' , 0 )')
82    FORMAT(' INCIDENT ANGLE INDEGREES.',I4)
86    FORMAT('+',62X,F8.4)
87    FORMAT(62X,' X COORD OF COLLECTOR')
20    END
```

```
*
*PROGRAM:       VERN.FOR
*WRITTEN BY:    R.W.ELLIOTT.

      SUBROUTINE      VERN    (X,R1,Q,V)       !THESE VARIABLES HAVE BEEN TRANSFERED FROM THE MAIN PROGRAM.
      A=1                                      !THE PARAMETERS FOR THE QUADRATIC EQUATION.
      B=(-2*R1)
      C=X**2
      DIS=SQRT(B**2-4*A*C)                     !THE SQUARE ROOT OF THE DISCRIMINANT OF THE QUADRATIC EQUATION.
      Y=(-B-DIS)/2*A                           !THE VERTICAL DROP OF THE INCIDENT COORDINATE FROM THE TOP.
      V=X*COSD(Q-270)-Y*SIND(Q-270)            !THE VERNIER READING V FOR THE COLLECTOR TURNED THROUGH AN ANGLE
                                               !OF LQ DEGREES TO THE VERTICAL WITH A LATERAL DISPLACEMENT OF X.
      RETURN                                   !RETURN TO MAIN PROGRAM.
      END                                      !PHYSICAL END OF PROGRAM.
```

APPENDIX C

```
*
*PROGRAM      :RWE11.FOR
*WRITTEN BY   :R.W.ELLIOTT.

      DOUBLE PRECISION  A,B,C,G,F,X,Y,X1,X2,Y1,Y2,YT,XI,XX,CK,Z,R      !THESE VARIABLES USE VERY HIGH ACCURACY SO AS TO
      DOUBLE PRECISION  DIS,R2,RT,RI,RR,RAY,FNQ,FSNQ,RFFM,RFFC,RN,RP  !OVERCOME THE PROBLEM OF RAYS WHICH PASS NEAR
      DOUBLE PRECISION  COSD,ASIN,SIND,TAND,DATAN,DSQRT,DABS,RAYR,DSIN,DCOS     !BOUNDARIES OR BOUNDARY INTERCEPTS.
      DIMENSION ANSWER(13,8),TABLE(20,15),TABTOT(20,15)      !CREATE TWO 3 DIMENSIONAL ARRAYS  WHICH ARE 13X8 AND 20X15.
      DIMENSION      COL(20),COLP(20),COLPT(20)      !CREATE THREE ONE DIMENSIONAL ARRAYS.
      INTEGER*4      D,TT,J,I,JT,IX
      OPEN(UNIT=32,NAME='ENERGY_TEMP.DAT',TYPE='UNKNOWN')     !Data file to store energy generation array.

      U=1.526                         !THE REFRACTIVE INDEX OF THE 'HYPO 2000'.
      N=1
      S=0                             !S IS A PARAMETER FOR LATERAL MOVEMENT OF THE SIDE SURFACES.
      L=0                             !L IS A PARAMETER FOR CHANGING THE ANGLE OF THE LIGHT RAYS.
      P=1000000                       !ANY RAY LONGER THAN 10 METERS IS IGNORED (HARDLY ANY).
      DO 100 IT=9,9                   !A LOOP TO CHANGE THE RADIOUS OF THE TOP SURFACE.
      R1=5*2**IT-10                   ! -F IS THE CENTRE OF THE TOP SURFACE.
                                      !R1 IS THE RADIOUS OF THE TOP SURFACE.
      DO 200 IS=4,4                   !A LOOP TO CHANGE THE RADIOUS OF THE SIDE REFLECTING SURFACE
      G=6-4*2**IS                     !G IS A PARAMETER FOR THE SIDE REFLECTING SURFACES.
      DO 700 IH=15,15                 !A LOOP TO REDUCE THE HEIGTH, WITHOUT CHANGING THE RADIOUS.
      H=IH                            !THE Y AXIS INTERCEPT OF THE TOP SURFACE.
      F=R1-H                          !ADJUSTMENT OF F WHEN TOP SURFACE IS LOWERED.
      FF=(-F)                         !THE Y COORDINATE OF THE CENTRE OF THE TOP SURFACE.
      DO  600  S=1,1                  !A LOOP TO MOVE OUT THE SIDES WITHOUT CHANGING THE RADIOUS.
                                      !PARAMETER FOR CHANGING THE SIDES CENTRE WITH SAME RADIOUS.
      R2=DABS(G)                      ! R2 IS THE RADIOUS OF THE SIDE SURFACES.
      GG=R2+S                         ! X COORDINATES OF THE CENTRES OF THE TWO SIDE REFLECTING
      GGG=(-GG)                       ! SURFACES.
      IF(DABS(F).LE.0.0001)  GO TO  700     !IF THE CENTRE OF THE TOP IS ON X AXIS EQUATIONS ARE UNTRUE.
      CK=(H**2+2*F*H-S*(2*G-S))/(2*F)       !THE CONSTANTS IN THE QUADRATIC EQUATION THAT WILL EVALUATE
      A=1+(G-S)**2/F**2                     !THE INTERCEPT BETWEEN THE SIDE SURFACES AND THE TOP SURFACE
      B=2*(G-S)*(CK+F)/F
      C=CK**2+2*F*CK-H**2-2*F*H
      IF(B**2-4*A*C)200,2,2                 !IF THE DISCRIMINANT IS NEGATIVE THEN NO INTERCEPT.
2     CALL QUADRT ( A,B,C,X)                !SUBROUTINE TO EVALUATE A QUADRATIC ; AND GIVE +VE ROOT.
      IF(F.GT.0)  X=(-B-DSQRT(B**2-4*A*C))/(2*A)   !IF CENTRE OF TOP SURFACE IS NEGATIVE WE NEED OTHER ROOT.
      Y=(G-S)*X/F+CK                        ! Y COORDINATE OF THIS INTERCEPT.
      IXQ=X/2                               !CONDITION THAT CONCENTRATION IS > A FACTOR OF TWO.
      IF(IXQ.LT.S)  GO TO 700               !IF SIDES ARE TO FAR APART CHANGE THE SHAPE.
      TYPE78                                !PRINT OUT OF THE REFERENCES AND COORDINATES OF THIS SHAPE
      TYPE79,FF                             !IE. THE CENTRES, RADII AND INTERCEPTS.
      TYPE80
      TYPE81,GGG,GG
      TYPE 50,R1
      TYPE 51, R2
      TYPE 52
      X=(-X)
      TYPE53 , X , Y
      X=(-X)
      TYPE 54, X , Y
      TYPE 56
      TYPE 57
      TYPE 58
      TYPE 59
      TYPE 69
      TYPE 60
      TYPE70                                !THIS LOOP DETERMINES THE WIDTH OF THE COLLECTOR PLATE.
      DO 310 IQ=1,IXQ,1                     !Q IS THE RIGHT HAND X COORDINATE OF THE COLLECTOR PLATE.
      Q=IQ                                  !TEST IF COLLECTOR WIDTH IS < DISTANCE BETWEEN SIDES.
      IF(Q.LT.S)  GO TO  310                ! QQ IS THE LEFT HAND X COORDINATE OF THE COLLECTOR.
      QQ=(-Q)
      YT=(S*(2*G-S)-2*(G-S)*Q-Q**2)         !THE Y COORDINATE OF THE COLLECTOR PLATE.
      YT=DSQRT(YT)
```

```
      ZQ=Q-QQ                                 ! ZQ IS THE WIDTH OF THE COLLECTOR.
      TYPE75                                  !PRINT THE REFERENCES FOR THE COLLECTOR.
      TYPE76,Q,QQ
      TYPE 61
      TYPE 71
      CALL VOLUME (R1,R2,X,Y,Q,YT,F,S,VOL)    !SUBROUTINE TO OBTAIN THE INTERNAL VOLUME OF THE COLLECTOR.
      L=0                                     !L IS A PARAMETER FOR THE DIFFERENT INCIDENCE RAYS.
      TENEGY=0                          !A VARIABLE TO CALCULATE THE ENERGY ABSORBED IN THE COLLECTOR.
      DO 40 I=1,20
      COLPT(I)=0
40    CONTINUE
      DO 1000 I=1,15                    !A LOOP TO CREATE AN EMPTY ARRAY.
      DO 1100 J=1,20
      TABTOT(J,I)=0
1100  CONTINUE
1000  CONTINUE
      DO 300 LQ=240,300,5                     ! TO CHANGE THE ANGLE AT WHICH THE RAYS ENTER THE COLLECTOR.
      DO 800 I=1,20
      COL(I)=0
      COLP(I)=0
      DO 900 J=1,15
      TABLE(I,J)=0
900   CONTINUE
800   CONTINUE
      REF=0                                   !REF IS THE NUMBER OF REFLECTIONS. AT START SET TO ZERO.
      TOTENY=0
      IX=99*X                                 !RANGE OF INCIDENCE RAYS ON THE TOP SURFACE MAGNIFIED BY 99.
      XZ=0.9999*X                             !CONDITION : COORDINATE FOR LIMIT OF  BOUNDARY ACCURACY.
      L=L+1                                   !FIRST VALUE OF L FOR FIRST CONSIDERED INCIDENCE ANGLE.
      ANSWER(L,1)= LQ                         !ANGLE OF INCIDENCE FOR EACH  VALUE OF L.
      ANSWER(L,2) = 0                         !NUMBER OF RAYS INCIDENT ON TOP SURFACE BEING CONSIDERED.
      ANSWER(L,3) = 0                         !NUMBER OF SIDE REFLECTIONS FOR THIS SHAPE AT THIS ANGLE.
      ANSWER(L,4) = 0                   !NUMBER OF TOTAL INTERNAL REFLECTIONS FOR THIS SHAPE AT THIS ANGLE.
      ANSWER(L,5) = 0                   !THE FRACTION OF INCIDENT ENERGY REACHING COLLECTOR AT THIS ANGLE.
      ANSWER(L,6) = 0                   !NUMBER OF RAYS REACHING THE COLLECTOR AFTER ABSORBTION LOSES.
      ANSWER(L,7) = 0                   !NUMBER OF RAYS INCIDENT REACHING THE COLLECTOR.
      ANSWER(L,8)=0                     !FRACTION OF INCIDENT RAYS REACHING THE COLLECTOR AT THIS ANGLE.
      DO 455 IXI=IX,(-IX),-1            !A LOOP TO CONSIDER EACH RAY, LEAVING 1% OF WIDTH AT BOUNDARIES.
*     TYPE*,IXI
      XI=IXI                            ! X COORDINATE OF INCIDENT RAY MAGNIFIED BY 100 TIMES.
      X1=XI/100                         ! X COORDINATE OF THE INCIDENT RAY. EACH RAY 1/100TH OF A CM APART.
      TRR=90                            ! PARAMETER FOR TOTALLY INTERNALLY REFLECTED RAY. PRESET TO
                                        ! LARGE VALUE SO AS THIS CONDITION WILL NOT EJECT RAY UNLESS RESET
                                        ! BY TOTAL INTERNAL REFLECTING CONDITION.
      TIR=0                             ! COUNTS THE NUMBER OF TIMES RAY TOTALLY INTERNALLY REFLECTED.
      TRAP=0                            !CONDITION. IF TRAP=0 THEN RAY HAS NOT REACHED THE COLLECTOR.
      RLOP=0.1                          !ASSUME 5.6% ABSORPTION IN FIRST 1MM. REFLECTION LOSSES TO BE ADDED.
      REF=0                             !RESET NO OF REFLECTIONS TO ZERO FOR NEW RAY.
******************************************
*     RAY STARTING FROM TOP SURFACE   *
******************************************
      JT=4                              !IF JT=4 THEN 'TAB' WILL ADD 3% TO FIRST SQUARE OF ABSORPTION MESH.
      J=4                               !IF J=4 THEN RAY IS ENTERING THE TOP SURFACE.
      D=1                               !IF D=1 THEN RAY IS COMING FROM TOP SURFACE AND RAY MUST BE TESTED
                                        !FOR INTERCEPTION ON SIDE SURFACES BEFORE TESTING AT THE COLLECTOR.
      A=1                               !PARAMETERS OF THE EQUATION FOR THE Y VALUE OF THE INCOMING RAY.
      B=2*F
      C=X1**2-H**2-2*F*H
1     CALL QUADRT (A,B,C,Y1)             !Y1 IS THE Y COORDINATE OF THE STARTING POINT OF THE RAY.
      IF(X1.EQ.0) THEN                   !AT THIS POINT THE NORMAL 'FNQ' IS VERTICAL THEREFORE SET FNQ=90°
              FNQ=90                     !SET THE NORMAL OF THE TOP SURFACE TO 90°.
      ELSE                                      !RETURN TO PROGRAM TO CALCULATE THE REFRACTED RAYS ANGLE (RAY).
              FNQ=DATAN((Y1+F)/X1)       !THE NORMAL TO THE TOP SURFACE IN RADIANS ANTICLOCKWISE FROM X AXIS.
              FNQ=FNQ*180/3.141592653589793238   !THE NORMAL TO THE TOP SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS.
              IF(FNQ.LT.0)  FNQ=FNQ+180
      ENDIF
```

```
3       I=LQ-180                                   !I IS A PARAMETER FOR THE INCIDENT RAY.
        IF(I.LE.FNQ)  RI=FNQ-I                     !RI IS THE ANGLE OF INCIDENCE FOR THE INCOMING RAY.
        IF(I.GT.FNQ)  RI=I-FNQ
        IF(RI.GE.90)  GO TO  450             !IF THE INCIDENCE ANGLE IS GREATER THAN 90' THEN COORDINATE IS IN SHADOW.
        RR=ASIN(SIND(RI)/U)                                 !REFRACTED ANGLE IN RADIANS.
        RR=RR*180/3.14159265358979323 8                     !REFRACTED ANGLE IN DEGREES.
        IF(I.LE.FNQ)  RAY=FNQ-RR+180                        !RAY IS THE ANGLE THE LIGHT BEAM MAKES WITH THE X AXIS.
        IF(I.GT.FNQ)  RAY=FNQ+RR+180
        IF((RAY.EQ.90).OR.(RAY.EQ.270))  X2=X1              !IF RAY IS VERTICAL ITS SLOPE IS INFINITE SO PUT X2=X1.
                                                            !IF RAY IS VERTICAL PUT X2=X1 AND FIND THE Y INTERCEPT.
        RN=RR-RI                                                  !THE DIFFERENCE BETWEEN THE INCIDENT AND REFRACTED ANGLES.
        RP=RR+RI                                                  !THE ADDITION OF THE INCIDENT AND REFRACTED ANGLES.
        IF (RN.LE.0.1) THEN
              R=((U-1)/(U+1))**2
        ELSE
              R=(((SIND(RN))**2/(SIND(RP))**2)+((TAND(RN))**2/(TAND(RP))**2))/2        !THE REFLECTANCE ON THE TOP SURFACE.FRESNELL
RELATIONSHIP.
        ENDIF
        RLOP=10**((84.6+R*100-94.4)/9.8)                    !THE APPARENT LENGTH OF THE RAY DUE TO REFLECTION ON THE TOP SURFACE.
        IF(RAY.EQ.90)  GO TO  12                            !IF RAY+90 ONLY INTERCEPT IS WITH THE TOP SURFACE.
        IF(RAY.EQ.270)  GO TO  17                           !IF RAY=270 THEN RAY CAN ONLY BE COMING FROM THE TOP SURFACE,M
*********************************
*       RAY STARTING TREK       *
*********************************
33      RAYR=RAY*3.14159265358979323 8/180
        RFFM=DSIN(RAYR)/DCOS(RAYR)                 !FIND THE SLOPE OF THE RAY  (RFFM).
        RFFC=Y1-X1*DSIN(RAYR)/DCOS(RAYR)           !FIND THE INTERCEPT OF THE RAY  (RFFC).
        IF((RAY.LT.90).AND.(J.EQ.2))  GO TO  88    !IF J=2 THEN RAY IS COMING FROM R.H.S. AND WITH RAY < 90'IT CAN ONLY
                                                   !INTERCEPT WITH THE TOP SURFACE.
        IF((TT.EQ.1).AND.(D.EQ.0))  GO TO  9       !D=0 MEANS THE RAY MUST BE COMING FROM THE SIDE SURFACES. TT=1 MEANS
                                                   !RAY < 180' THEREFORE IMPOSSIBLE INTERCEPT WITH COLLECTOR.
        IF(D.EQ.1)  GO TO  21                      !TEST THE SIDE SURFACES BEFORE THE COLLECTOR FOR RAY INTERSECTION
*****************************************                 !BECAUSE RAY IS COMING FROM  THE TOP SURFACE.
*       RAY INTERCEPT WITH COLLECTOR    *
*****************************************
19      X2=(-RFFC/RFFM)                            !X2 IS THE RAY INTERCEPT ON THE X AXIS.
17      IF((DABS(X2)-S).LT.0.0001)  THEN           !THE RAY ENTERS THE COLLECTOR.
              Y2=YT                                       !FIND THE Y COORDINATE OF THE RAY ON THE COLLECTOR SURFACE.
              IF(X2.GT.S)     THEN
                    X2=S-0.0001                           !IF THE NEW X COORDINATE IS OUTSIDE THE COLLECTOR RANGE.
              ELSE
                    IF (X2.LT.(-S))THEN
                    X2=0.0001-S                           !USE ITS LIMITING VALUES.
                    ENDIF
              ENDIF
              TRAP=1                                      !TRAP=1 IS THE VARIABLE TO SHOW THE RAY HAS REACHED THE COLLECTOR.
              GO TO  14                                   !NOW FIND THE TOTAL LENGTH OF THE RAY IN THE LIQUID.
        ENDIF
        X2=X1                                      !REPLACE X2 WITH ORIGINAL VALUE SINCE THIS VALUE IS INCORRECT.
        D=0
9       IF(J.EQ.1)  GO TO  44                      !RAY COMING FROM L.H.S. THEREFORE TEST FOR INTERCEPT ON R.H.S.
*********************************
*       INTERCEPT L.H.S.        *
*********************************
                                                   !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
        A=1+RFFM**2                                !THE L.H.S.  (LEFT HAND SIDE SURFACE).
        B=2*RFFM*RFFC-2*(G-S)
        C=RFFC**2-2*(G-S)*S-S**2                          !NO INTERCEPT ON L.H.S. AND RAY COMING FROM TOP SURFACE ON L.H.S.
        IF((B**2.LT.4*A*C).AND.(D.EQ.1))  GO TO  19  !SO TRY COLLECTOR AND SET PARAMETER  D TO ZERO. TEST COMPLETE.
                                                   !NO INTERCEPT ON L.H.S. SO TRY R.H.S.  (RIGHT HAND SIDE SURFACE).
        IF(B**2.LT.4*A*C)  GO TO  44               !SUBROUTINE TO FIND THE LARGEST ROOT OF A QUADRATIC.
        CALL QUADRT (A,B,C,X2)
        IF((RFFM.LT.0).AND.(J.GE.3)) CALL QUADNG(A,B,C,X2)!WITH AN INTERCEPTION ON THE L.H.S. AND RAY -VE FIND THE LEAST ROOT.
                                                          !IF SLOPE IS -VE AND INTERCEPT IS NOT ON R.H.S. FIOND SMALLEST ROOT.
                                                          !RAY INTERCEPT WITH L.H.S. OUTSIDE BOUNDARY CONDITIONS.
        IF((X2.LT.-X).AND.(D.EQ.1))  THEN                 !D=0 MEANS SIDE SURFACES HAVE BEEN TESTED FOR INTERCEPTION OF RAY.
              D=0                                         !PRIOR TO IT BEING TESTED AT THE COLLECTOR.
```

```
      FSNQ=FSNQ*180/3.141592653589793238          !THE NORMAL TO THE SIDE SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS
      IF((FSNQ.LT.180).AND.(FSNQ.GT.0)) GO TO 4   !IF NORMAL IN CORRECT QUADRANTS FIND THE REFLECTED RAY.
      FSNQ=FSNQ+180                               !CORRECT THE NORMAL FOR INCORRECT QUADRANTS.
4     IF(J.EQ.2) THEN                             !IF THE INTERCEPT IS ON THE R.H.S. SURFACE FIND ITS REFLECTED RAY.
            CALL  RAYJ2(RAY,FSNQ,TT)              !FIND THE REFLECTED RAY ANGLE FOR R.H.S SURFACE AND SET TT.
      ELSE
            CALL  RAYJ1(RAY,FSNQ,TT)              !FIND REFLECTED RAY ANGLE FOR L.H.S. SURFACE AND SET PARAMETER TT.
      ENDIF                                       !SET THE DIRECTION PARAMETER TT=1 FOR ALL RAY TRAVELLING UPWARDS.
      X1=X2                                       !THE FINAL COORDINATES OF THE OLD RAY BECOME THE START COORDINATES
      Y1=Y2                                       !OF THE NEW RAY.
      GO TO  33                                   !FIND THE SLOPE OF THE NEW RAY AND FIND THE NEXT INTERCEPT.
25    X1=X2                                       !THE FINAL COORDINATES OF THE OLD RAY BECOMES THE INITIAL
      Y1=Y2                                       !COORDINATES OF THE NEW RAY.
      RAYR=RAY*3.141592653589793238/180
      RFFM=DSIN(RAYR)/DCOS(RAYR)                  !FIND THE SLOPE OF THE RAY  (RFFM).
      RFFC=Y1-X1*DSIN(RAYR)/DCOS(RAYR)            !FIND THE INTERCEPT OF THE RAY  (RFFC).

*****************************************
*     INTERCEPT WITH TOP SURFACE        *
*****************************************

88    A=1+RFFM**2                                 !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
      B=2*F*RFFM+2*RFFM*RFFC                      !THE TOP SURFACE.
      C=RFFC**2-H**2-2*F*H+2*F*RFFC
      IF(RFFM.LT.0) THEN                          !IF THE SLOPE OF THE RAY IS -VE THEN THE SMALLEST ROOT IS REQUIRED.
            CALL QUADNG (A,B,C,X2)                !IF SLOPE OF RAY IS -VE THEN THE SMALLEST ROOT IS REQUIRED.
            IF((J.GE.3).AND.(DABS(X2-X1).LE.0.0001))  CALL QUADRT(A,B,C,X2) !POSSIBLE EXCEPTIONS WHEN LARGEST ROOT IS REQUIRED.
      ELSE
            CALL QUADRT (A,B,C,X2)                !SUBROUTINE TO FIND THE LARGEST ROOT OF A QUADRATIC EQUATION.
            IF((J.GE.3).AND.(DABS(X2-X1).LE.0.0001))  CALL QUADNG(A,B,C,X2) !IF RAY STARTS ON THE TOP SURFACE MAKE SURE THE
                                                  !START COORDINATES ARE NOT THE SAME AS THE FINISH.
      ENDIF
      IF((X2.GT.X).OR.(X2.LT.(-X)))  GO TO  33    !IF INTERCEPT NOT WITHIN THE SHAPE THEN TRY A SIDE SURFACE.
12    A=1                                         !THE PARAMETERS OF THE QUADRATIC EQUATION TO FIND THE Y COORDINATE
      B=2*F                                       !OF THE INTERCEPT WITH THE TOP SURFACE.
      C=X2**2-H**2-2*F*H
      CALL  QUADRT (A,B,C,Y2)                     !SUBROUTINE TO FIND THE LARGEST VALUE OF A QUADRATIC EQUATION.
      IF(X2.GT.XZ.OR.X2.LT.-XZ) GO TO 14          !IF RAY PASSES OUTSIDE THESE THESE LIMITS ASSUME RAY HAS ESCAPED.
      IF(Y2.LT.Y)  GO TO  33                      !IF NEW INTERCEPT IS OUTSIDE THE SHAPE THEN TRY A SIDE SURFACE.
      IF(DABS(Y2-RFFM*X2-RFFC).GE.0.1) GO TO 33   !A TEST TO MAKE SURE THE COORDINATE FOUND ARE OF A POINT ON THE RAY.
      FNQ=DATAN((Y2+F)/X2)                        !FIND THE NORMAL OF THE TOP SURFACE AT THE POINT OF INTERCEPTION.
      FNQ=FNQ*180/3.141592653589793238            !THE NORMAL TO THE TOP SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS.
      IF(FNQ.LT.0)  FNQ=FNQ+180                   !MAKE THE NORMAL TO THE TOP SURFACE LIE IN THE 1ST OR 2ND QUADRANTS.
      RR=DABS(RAY-FNQ)                            !THE REFLECTED RAY IS EQUAL TO THE INCIDENCE RAY.
      IF(RR.GT.180)  RR=360-RR                    !THE REFLECTED RAYS ANGLE MUST BE ACUTE.
      IF(RR.LT.40)  GO TO 63                      !IF THE INCIDENCE ANGLE IS<40' THEN RAY IS NOT INTERNALLY REFLECTED.
      J=3
      D=1
      TIR=TIR+1
      CALL  TAB(J,X1,Y1,X2,Y2,RFFM,RFFC,RLOP,TABLE,TRAP)  !INTERCEPT ON TOP SURFACE WITH TOTAL INTERNAL REFLECTION.
      IF(RLOP.GT.P)  GO TO 450
      ANSWER(L,4)=( ANSWER(L,4)+1)
      IF((RAY.GT.FNQ).AND.(RAY.LT.270))  THEN
            RAY=FNQ-RR+180                        !THE ANGLE OF TOTALLY INTERNALLY REFLECTED RAY ON THE TOP SURFACE.
      ELSE
            RAY=FNQ+RR+180
      ENDIF                                       !CORRECT THE RAY TO BE IN BETWEEN 0' AND 360'.
      IF(RAY.GE.360)  RAY=RAY-360
      IF (RAY. LE.180.AND.RAY.GE.0) THEN
            TT=1
      ELSE
            TT=0
      ENDIF
      GO TO  25

*******************************
```

```
          GO TO 19                          !THE RAY CAN NOW BE TESTED FOR INTERCEPT WITH COLLECTOR.
      ENDIF
      IF(X2.LT.-X)  THEN                    !INTERCEPT WITH L.H.S. OUTSIDE BOUNDARY CONDITIONS. TRY R.H.S.S.
          X2=X1                             !REPLACE NEW COORDINATE WITH OLD VALUE SINCE IT IS NOT VALID.
          GO TO 44                          !INTERCEPT WITH L.H.S. OUTSIDE BOUNDARY CONDITION .TRY R.H.S.S.
      ENDIF
      J=1                                   !RAY HAS LIGITIMATE INTERCEPTION WITH L.H.S.
      D=0                                   !DO NOT TEST SIDE SURFACES BEFORE THE COLLECTOR. OR TEST COMPLETED.
      GO TO  66                             !FIND Y COORDINATE  AND UP DATE RESULTS THEN FIND NEXT REFLECTION.
*********************************           !SO TEST THE COLLECTOR FOR NEXT INTERCEPTION THEN R.H.S AND L.H.S.
*     RAY FROM TOP SURFACE      *
*********************************
21    IF(X1.LT.0)  GO TO  9                 !IF THE RAY IS COMING FROM THE L.H.S.TOP SURFACE  THEN TEST
                                            !INTERCEPT WITH L.H.S. SURFACE BEFORE R.H.S. SURFACE.
44    IF((RAY.GE.90).AND.(RAY.LE.180))  GO TO  88   !IF 90<RAY<180 THEN RAY CAN NOT POSSIBLY INTERCEPT WITH R.H.S.
                                            !THEREFORE TEST INTERCEPT WITH TOP SURFACE.
      IF(J.EQ.2)  GO TO  88                 !RAY COMING FROM R.H.S.  TEST NEXT INTERCEPTIWITH WITH TOP SURFACE.
*********************************
*     INTERCEPT R.H.S.          *
*********************************
      A=1+RFFM**2                           !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
      B=2*RFFM*RFFC+2*(G-S)                 !THE R.H.S.   (RIGHT HAND SIDE SURFACE).
      C=RFFC**2-S*(2*G-S)
      IF((B**2.LT.4*A*C).AND.(D.EQ.1))  GO TO  19   !TEST SHOWS THAT WHEN RAY IS COMING FROM THE RIGHT HAND TOP SURFACE
                                            !THERE IS NO INTERCEPTION WITH THE R.H.S. SURFACE. SO NOW
                                            !TEST INTERCEPTION WITH COLLECTOR AND SET D=0 TO SHOW TEST COMPLETE.
      IF(B**2.LT.4*A*C)  GO TO 88           !NO INTERCEPT WITH R.H.S.  NEXT TEST INTERCEPTION WITH TOP SURFACE.
      CALL QUADRT (A,B,C,X2)                !INTERCEPTION WITH R.H.S. SO CALCULATE X COORDINATE.
      IF(X2.GT.X1) CALL QUADNG(A,B,C,X2)    !IF RAY IS IN FOURTH QUADRANT THE SMALLEST INTERCEPT IS REQUIRED.
      IF((X2.GT.X).AND.(D.EQ.1))  GO TO  19 !INTERCEPT OUTSIDE THE SHAPE .TEST COMPLETE. NEXT TEST COLLECTOR.
      IF(X2.GT.X)  GO TO  88                !INTERCEPT OUTSIDE THE SHAPE. SO NEXT TEST TOP SURFACE.
      J=2                                   !RAY HAS LIGITIMATE INTERCEPTION WITH R.H.S.
      D=0                                   !DO NOT TEST SIDE SURFACES BEFORE THE COLLECTOR; OR TEST COMPLETED.

*************************************************
*     FIND THE Y COORD. EITHER L. OR R.         *
*************************************************

66    IF(J.EQ.1)  THEN                      !FIND Y COORDINATE FOR THE L.H.S. SURFACE INTERCEPT.
93        Y2=DSQRT(S**2+2*(G-S)*S+2*(G-S)*X2-X2**2)   !THE Y COORDINATE FOR THE L.H.S. SURFACE INTERCEPT.
      ELSE
          Y2=DSQRT(S*(2*G-S)-2*(G-S)*X2-X2**2)        !THE Y COORDINATE FOR THE R.H.S. SURFACE INTERCEPT.
      ENDIF
      IF ((J.LE.2).AND.((DABS(X2)-Q).LT.0.0001)) THEN   !TEST TO SEE IF INTERCEPT IS WITHIN THE COLLECTOR.
          Y2=YT                             !FIND THE Y COORDINATE OF THE RAY ON THE COLLECTOR SURFACE.
          X2=(Y2-RFFC)/RFFM                 !FIND THE Y COORDINATE OF THE RAY FOR THIS VALUE OF Y.
          IF(X2.GT.Q)     THEN              !IF THE NEW X COORDINATE IS OUTSIDE THE COLLECTOR RANGE.
              X2=Q-0.0001
          ELSE
              IF (X2.LT.QQ) THEN                      !USE ITS LIMITING VALUES.
                  X2=QQ+0.0001
              ENDIF
          ENDIF
          TRAP=1                            !TRAP=1 IS THE VARIABLE TO SHOW THE RAY HAS REACHED THE COLLECTOR.
          GO TO  14                         !FIND THE TOTAL LENGTH OF THE RAY IN THE LIQUID BEFORE IT REACHES
      ENDIF                                 !                                               THE COLLECTOR.
96    REF=REF+1                             !ADD ONE TO THE NUMBER OF SIDE REFLECTIONS.
      CALL  TAB(J,X1,Y1,X2,Y2,RFFM,RFFC,RLOP,TABLE,TRAP)   !INTERCEPT WITH SIDE SURFACE.
      IF(RLOP.GT.P)  GO TO 450              !IF RAY IS TOO LONG ITS BEEN MOSTLY ABSORBED SO NEGLECT REMAINDER.
      IF((X2.GT.XZ).OR.(X2.LT.-XZ))  GO TO  450   !IF RAY PASSES OUTSIDE THESE LIMITS ASSUME RAY HAS ESCAPED.
      IF(X2.LT.0)  THEN
          XX=Y2/(X2-(G-S))                  !FIND THE NORMAL OF THE L.H.S. SURFACE AT THE POINT OF INTERCEPTION.
      ELSE
          XX=Y2/(X2-(S-G))                  !FIND THE NORMAL OF THE R.H.S. SURFACE AT THE POINT OF INTERCEPTION.
      ENDIF
      FSNQ=DATAN(XX)                        !THE NORMAL TO THE SIDE SURFACE IN RADIANS ANTICLOCKWISE FROM X AXIS
```

```
*       RAY HAS ESCAPED         *
*********************************

63      TRR=RR
14      CALL  TAB(J,X1,Y1,X2,Y2,RFFM,RFFC,RLOP,TABLE,TRAP)!INTERCEPT TOP OR BOTTOM.
        IF( RLOP.GT.P) GO TO 450
        IF(TRR.LT.40)  GO TO  450
        IF(TRAP.EQ.0)  GO TO  450

****************************************
*       RAY REACHES RECEIVER PLATE      *
****************************************

        CALL    TRAP2(X2,Y2,RLOP,COL)                  !SUBROUTINE TO FIND THE DISTRIBUTION OF ENERGY AT THE COLLECTOR.
        ANSWER(L,6)=ANSWER(L,6)+((84.6-9.8*LOG10(RLOP))/100)    !FRACTION OF ENERGY REACHING COLLECTOR AT THIS ANGLE
                ANSWER(L,7)=ANSWER(L,7)+1                                 !NO OF RAYS REACHING THE COLLECTOR AT THIS ANGLE.
450             ANSWER(L,2)=ANSWER(L,2)+1                           ! COUNTS NUMBER OF RAYS INCIDENT ON TOP SURFACE.
                ANSWER(L,3)=ANSWER(L,3)+REF                  ! COUNTS TOTAL NUMBER OF SIDE REFLECTIONS FOR EACH INCIDENCE ANGLE.
455             CONTINUE
                ANSWER(L,5)=ANSWER(L,6)/ANSWER(L,2)          !FRACTION OF INCIDENT ENERGY REACHING THE COLLECTOR AT THIS ANGLE.
                ANSWER(L,8)=ANSWER(L,7)/ANSWER(L,2)          !FRACTION OF INCIDENT RAYS REACHING THE COLLECTOR AT THIS ANGLE
                CALL TABCNT (TABTOT,TABLE,TOTENY,TENEGY,ANSWER,L) !SUBROUTINE TO CALCULATE TOTAL ENERGY ABSORBED IN THIS SHAPE.
                TYPE 62,(ANSWER(L,J),J=1,8)
                DO 94 N=15,1,-1
                TYPE 82,((TABLE(M,N),M=6,13),TABLE(20,N))
94              CONTINUE
                DO 101 I=1,18                                !LOOP TO FIND THIS ENERGY AS A PERCENTAGE.
                COLP(I)=COL(I)/ANSWER(L,2)*100               !ARRAY WTIH ENERGY AS A PERCENTAGE.
                COLPT(I)=COLPT(I)+COLP(I)
                COLP(20)=COLP(20)+COLP(I)
101             CONTINUE
                COLPT(20)=COLPT(20)+COLP(20)
                TYPE82,((COLP(I),I=6,13),COLP(20))

                TYPE85,TOTENY
                TYPE86,COLP(20)                              !TOTENY IS THE PERCENTAGE OF INCOMING ENERGY ABSORBED IN THE LIQUID.
                TYPE87,(TOTENY+COLP(20))
**************************************************
*       Create energy generation file           *
**************************************************

                IF (LQ.GE.270) THEN                          !Choose angles of incidence..
                        DO 194 N=15,1,-1
                        WRITE(32,2000) (TABLE(M,N),M=6,13)
194                     CONTINUE

                        WRITE(32,2000) (COLP(I),I=6,13)
                        WRITE(32,89) LQ,COLP(20)
                ENDIF

300             CONTINUE
                CALL EFFY (ANSWER,R1,R2,FF,GG,X,YT,H,ZQ,VOL)
                DO 48 N=1,20
                COLPT(N)=COLPT(N)/L                          !CORRECT THE COLLECTOR ARRAY TO PERCENTAGES.
48              CONTINUE
                DO 98 N=1,15
                DO 99 M=1,20
                TABTOT(M,N)=TABTOT(M,N)/L                        !CORRECT THE TOTAL ENERGY IN THE COLLECTOR TO A PERCENTAGE.
99              CONTINUE
98              CONTINUE

                DO 97 N=15,1,-1
                TYPE82,((TABTOT(M,N),M=6,13),TABTOT(20,N))
97              CONTINUE
                TENEGY=TENEGY/L                              !CORRECT THE TOTAL ENERGY IN THE COLLECTOR TO A PERCENTAGE.
                TYPE82,((COLPT(I),I=6,13),COLPT(20))
```

```
            TYPE85,TENEGY
            TYPE86,COLPT(20)
            TYPE87,(TENEGY+COLPT(20))
310         CONTINUE
600         CONTINUE
700         CONTINUE
200         CONTINUE
100         CONTINUE
            GO TO  20
50          FORMAT (5X'LENGTH OF RADIUS OF TOP SURFACE',5X,F8.0)
51          FORMAT (5X'LENGTH OF RADIUS OF SIDE SURFACE',4X,F8.0)
52          FORMAT(5X'COORDINATES OF CURVED SURFACE INTERSECTION')
53          FORMAT(5X'( ',F6.2,' , ',F6.2,' )')
54          FORMAT('+'30X,'( ',F6.2,' , ',F6.2,' )')
56          FORMAT(5X'ANGLE OF RAY                                LQ.')
57          FORMAT(5X'X COORDINATE OF INCOMING RAY                C.O.R.')
58          FORMAT(5X'NUMBER OF SIDE REFLECTIONS                  N.O.S.R.')
59          FORMAT(5X'NUMBER OF TIMES BEAM TOTALLY INTERNALLY ')
69          FORMAT(5X,'REFLECTED ON  TOP SURFACE                  T.I.R.')
60          FORMAT(5X'INTENSITY AS A PERCENTAGE O F INCIDENT RAYS')
70          FORMAT('+'48X,' INTENSITY.')
61          FORMAT('-',' LQ.'5X'C.O.R.'5X'N.O.S.R.')
71          FORMAT('+'35X'T.I.R.'5X'RAY.ESC.'5X'INTENSITY.')
62          FORMAT(5X,/,8F10.3,/)
64          FORMAT('+'45X'ESCAPED.')
67          FORMAT('+'22X,F5.1)
68          FORMAT('+'65X,'TO LONG.')
72          FORMAT('+'45X,'COORDINATE IS IN SHADOW.')
73          FORMAT('+'32X,F6.1)
74          FORMAT('+'65X,F6.2)
75          FORMAT('0',' X  COORDINATES OF THE SOLAR TRAP')
76          FORMAT('+'35X,'ARE BETWEEN',F4.1,'  AND',F4.1)
78          FORMAT('-',' THE CENTRE OF THE  TOP CURVED ')
79          FORMAT('+'31X,'SURFACE IS ( 0 ,',F7.1,').')
80          FORMAT(' THE CENTRE OF THE SIDE CURVED SURFACE ARE ')
81          FORMAT('+'43X,'(',F5.1,' , 0 ) AND (',F5.1,' , 0 )')
82          FORMAT(25X,9F10.3)
85          FORMAT(5X' ENERGY ABSORBED IN HYVIS '4X,F5.2,'%')
86          FORMAT('+'45X,' ENERGY REACHING RECEIVER',4X,F5.2,'%')
87          FORMAT('+'85X,' TOTAL ENERGY GAINED IN COLLECTOR',4X,F5.2,'%')
89          FORMAT(5X,I3,5X,F5.2)
2000        FORMAT(5X,8F14.10)
20          END
```

```
*PROGRAM        :TAB.FOR
*WRITTEN BY     :R.W.ELLIOTT.

      SUBROUTINE        TAB (J,X1,Y1,X2,Y2,RFFM,RFFC,RLOP,TABLE,TRAP)
      DOUBLE PRECISION         X1,XX1,X2,XX2,Y1,YY1,Y2,YY2,X3,X4,Y3,Y4
      DOUBLE PRECISION         RFFM,RFFC,RFC,RLOP,ALONG,ALEN,ALNG,ALIR,ALOR
      DOUBLE PRECISION         SQRT,LOG10
      INTEGER*4                IX,IY,IXX1,IXX2,IYY1,IYY2
      DIMENSION TABLE(20,15)          ! DIMENSIONS OF TABLE OF RESULTS.
      XX1=X1+10                       ! TO MAKE SHAPE HAVE POSITIVE COORDINATES FOR TABLE ARRAY
      XX2=X2+10                       ! CONVENIANCE.
      YY1=Y1+1                        ! TO ALLOW FOR ZERO COORDINATES TO FIT IN THE ARRAY.
      YY2=Y2+1                        ! TO ALLOW FOR ZERO COORDINATES TO FIT IN THE ARRAY.
      RFC=RFFC-10*RFFM+1              ! TO GIVE THE RAY A LATERAL SHIFT OF TEN UNITS X1,X2 AND
                                      ! THE INTERCEPT HAVE TO BE CHANGED.
      IXX1=INT(XX1)                   ! TO FIND THE X COORDINATES OF THE ELEMENT IN WHICH THE RAY
      IYY1=INT(YY1)                   ! Y COORDS..
      IXX2=INT(XX2)                   ! STARTS AND FINISHES.
      IYY2=INT(YY2)                   ! Y COORDS..
      IF (ABS(IYY1-YY1).LE.0.0001) IYY1=IYY1-1          ! BORDER LINE CASE USE ELEMENT BELOW.
      IF (JT.EQ.4) THEN
            TABLE(IXX1,IYY1)=TABLE(IXX1,IYY1)+0.03      ! 3% ABSORBTION IN FIRST 1mm.
            JT=0
      ENDIF
      ALONG=RLOP                                        ! LENGTH OF RAY TO DATE.
      IF(XX1.LE.XX2.AND.YY1.LT.YY2)  GO TO  1           ! THESE STATMENTS ARE TO FIND IN WHICH WAY THE RAY IS GOING.
      IF(XX1.LE.XX2.AND.YY1.GT.YY2)  GO TO  4           ! SO AS TO CHOOSE THE CORRECT METHOD OF PLOTTING ITS PATH.
      IF(YY1.GE.YY2)  GO TO  3                          ! THIRD QUADRANT.




C**   **DIRECTION OF RAY IS IN THE SECOND QUADRANT.**

2     X3=XX2                          ! TO RETAIN THE FINAL COORDINATES OF THIS RAY IE. (XX2,YY2).
      Y3=YY2                          ! AND FOR CONVENIANCE WE SHALL START IN THIS SQUARE AND WORK BACKWARDS
      DO 10 N=IXX2,IXX1               ! A LOOP. TO ENTER THE RESULTS OF THE ENERGY ABSORBTION OF THE RAY
                                      ! IN EACH SQUARE INTO THE TABLE OF RESULTS.
50    IX=INT(X3)                            ! THE COORDINATES OF THE SQUARE IN WHICH THE RAY FINISHES.
      IY=INT(Y3)
      IF(Y3.EQ.IY)  IY=IY-1           ! IF THE COORDINATE IS ON THE LINE WE NEED THE SQUARE BELOW.
      X4=IX+1                         ! LAST X COORDINATE IN THIS SQUARE AND FIRST X COORDINATE OF THE NEXT
                                      ! SQUARE IF THE RAY PASSES OUT OF THE SIDE OF THE SQUARE.
      IF(X4.LT.XX1)  GO TO  20        ! TO TEST WETHER THE RAY STOPS SHORT OF THIS COORDINATE OR NOT.
      X4=XX1                          ! TO FIND THE RAY LENGTH IN THIS THE LAST SQUARE USE THE RAYS STARTING
      Y4=YY1                          !COORDINATES.
      GO TO  30                       ! TEST TO SEE IF THE RAY CAME INTO THIS SQUARE FROM BELLOW
                                      ! OR WETHER THE END OF THE RAY IS IN THIS SQUARE.
20    Y4=RFFM*X4+RFC                  ! TO FIND THE Y COORDINATE ON THE SIDE WALL.
30    IF(Y4.GE.IY)  GO TO 40          ! TEST IF RAY PASSES OUT THE SIDE OF THE SQUARE OR STARTED WITHIN IT.
      Y4=IY                           ! FIND THE COORDINATES AT WHICH THE RAY LEAVES THE BOTTOM OF SQUARE.
      X4=(Y4-RFC)/RFFM
      ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)              ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      ALOR=SQRT((X3-XX1)**2+(Y3-YY1)**2)            ! LENGTH OF RAY FROM THE STARTING POINT TO THE SQUARE LEAVING POINT.
      ALEN=ALONG+ALOR                               ! THE LENGTH OF THE ABSORBED RAY AT THE SQUARE LEAVING POINT.
      Z2=(-9.8*LOG10(ALEN)+84.6)                    ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE LEAVING THIS SQUARE.
      ALIR=ALEN-ALNG                                ! LENGTH OF RAY ON ENTERING THIS SQUARE.
      Z1=(-9.8*LOG10(ALIR)+84.6)                    ! TO FIND THE ABSORBED ENERGY OF THE RAY ON ENTERING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100   ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
```

```
      X3=X4                                    ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
      GO TO  50                                !FIND THE NEXT SQUARE THROUGH WHICH THE RAY PASSES.

40    ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)         ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      ALOR=SQRT((X3-XX1)**2+(Y3-YY1)**2)       ! LENGTH OF RAY FROM THE STARTING POINT TO THE SQUARE LEAVING POINT.
      ALEN=ALONG+ALOR                          ! THE LENGTH OF THE ABSORBED RAY AT THE SQUARE LEAVING POINT.
      Z2=(-9.8*LOG10(ALEN)+84.6)               ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE LEAVING THIS SQUARE.
      ALIR=ALEN-ALNG                           ! LENGTH OF RAY ON ENTERING THIS SQUARE.
      Z1=(-9.8*LOG10(ALIR)+84.6)               ! TO FIND THE ABSORBED ENERGY OF THE RAY ON ENTERING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100  ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                    ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
10    CONTINUE                                 ! FIND THE ABSORBTION OF THE RAY IN THE NEXT SQUARE THROUGH
                                               ! WHICH THE RAY PASSES.
      RLOP=RLOP+SQRT((X1-X2)**2+(Y1-Y2)**2)    !UPDATE THE LENGTH OF RAY.
*     TYPE 98,RLOP
      IF (TRAP.EQ.0) TABLE(IXX2,IYY2)=TABLE(IXX2,IYY2)+0.001*Z2      !ABSORBTION DUE TO REFLECTANCE.(10% OF Z2%=0.001*Z2).
      IF (TRAP.EQ.0) RLOP=10**(0.8633+0.9*LOG10(RLOP))               !APPARENT LENGTH OF RAY DUE TO REFLECTANCE.
*     TYPE 99,RLOP
      RETURN                                                         ! RETURN TO MAIN PROGRAM TO OBTAIN NEXT RAY.
```

```
C**   **DIRECTION OF RAY IS IN THE FOURTH QUADRANT.**

4     X3=XX1                          ! TO RETAIN THE STARTING COORDINATES OF THIS RAY IE. (XX1,YY1).
      Y3=YY1                          ! AND FOR CONVENIANCE WE SHALL START IN THIS SQUARE.
      DO 1000 NNN=IXX1,IXX2           ! A LOOP. TO ENTER THE RESULTS OF THE ENERGY ABSORBTION OF THE RAY
5000  IX=INT(X3)                              ! THE COORDINATES OF THE SQUARE IN WHICH THE RAY STARTS.
      IY=INT(Y3)
      IF(Y3.EQ.IY)  IY=IY-1           ! IF THE COORDINATE IS ON THE LINE WE NEED THE SQUARE BELOW.
      X4=IX+1                         ! LAST X COORDINATE IN THIS SQUARE AND FIRST X COORDINATE OF THE NEXT
      IF(X4.LT.XX2)  GO TO  2000      ! TO TEST WETHER THE RAY HAS STOPED SHORT OF THIS COORDINATE OR NOT.
      X4=XX2                          ! TO FIND THE RAY LENGTH IN THIS THE LAST SQUARE USE THE RAYS
      Y4=YY2                          !FINISHING COORDINATES.
      GO TO  3000                     ! TEST TO SEE IF THE RAY PASSES OUT OF THIS SQUARE FROM BELLOW

                                      ! BEFORE IT REACHES THE SIDE OR THE END OF THE RAY.
2000  Y4=RFFM*X4+RFC                  ! TO FIND THE Y COORDINATE ON THE SIDE WALL.
3000  IF(Y4.GE.IY)  GO TO  4000       ! IF TRUE THEN RAY HAS PASSED OUT OF THE SIDE OF THE SQUARE. OR HAS FINISHED.
      Y4=IY                           ! FIND THE COORDINATES WHERE THE RAY LEAVES THE BOTTOM OF THE SQUARE.
      X4=(Y4-RFC)/RFFM
      ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)           ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      Z1=(-9.8*LOG10(ALONG)+84.6)                ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE ENTERING THIS SQUARE.
      ALONG=ALONG+ALNG                           ! LENGTH OF RAY ON LEAVING THIS SQUARE.
      Z2=(-9.8*LOG10(ALONG)+84.6)                ! TO FIND THE ABSORBED ENERGY OF THE RAY ON LEAVING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100  ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                      ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
      GO TO  5000                                !FIND THE NEXT SQUARE THROUGH WHICH THE RAY PASSES.
4000  ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)           ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      Z1=(-9.8*LOG10(ALONG)+84.6)                ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE ENTERING THIS SQUARE.
      ALONG=ALONG+ALNG                           ! LENGTH OF RAY ON LEAVING THIS SQUARE.
```

```
      Z2=(-9.8*LOG10(ALONG)+84.6)                    ! TO FIND THE ABSORBED ENERGY OF THE RAY ON LEAVING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100    ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                          ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
1000  CONTINUE                                       ! FIND THE ABSORBTION OF THE RAY IN THE NEXT SQUARE THROUGH
      RLOP=RLOP+SQRT((X1-X2)**2+(Y1-Y2)**2)                     !UPDATE THE LENGTH OF THE RAY .
*     TYPE 98,RLOP
      IF (TRAP.EQ.0) TABLE(IXX2,IYY2)=TABLE(IXX2,IYY2)+0.001*Z2    !ABSORBTION DUE TO REFLECTANCE. (10% OF Z2%=0.001*Z2).
      IF (TRAP.EQ.0) RLOP=10**(0.8633+0.9*LOG10(RLOP))             !APPARENT LENGTH OF RAY DUE TO REFLECTANCE.
*     TYPE 99,RLOP
      RETURN                                                       ! RETURN TO MAIN PROGRAM TO OBTAIN NEXT RAY.




C**   **DIRECTION OF RAY IS IN THE FIRST QUADRANT.**

1     X3=XX1                      ! TO RETAIN THE STARTING COORDINATES OF THIS RAY IE. (XX1,YY1).
      Y3=YY1                      ! AND FOR CONVENIANCE WE SHALL START IN THIS SQUARE.
      DO 100 NN=IXX1,IXX2         ! A LOOP. TO ENTER THE RESULTS OF THE ENERGY ABSORBTION OF THE RAY
                                  ! IN EACH SQUARE INTO THE TABLE OF RESULTS.
500   IX=INT(X3)                         ! THE COORDINATES OF THE SQUARE IN WHICH THE RAY IS PASSING.
      IY=INT(Y3)
      X4=IX+1                     ! LAST X COORDINATE IN THIS SQUARE AND FIRST X COORDINATE OF THE NEXT
                                  ! SQUARE IF THE RAY PASSES OUT OF THE SIDE OF THE SQUARE.
      IF(X4.LT.XX2)  GO TO  200   ! TO TEST WETHER THE RAY STOPS SHORT OF THIS COORDINATE OR NOT.
      X4=XX2                      ! TO FIND THE RAY LENGTH IN THE LAST SQUARE USE THE RAYS FINISHING
      Y4=YY2                      !COORDINATES.
      GO TO  300                  ! TEST TO SEE IF THE RAY PASSES OUT OF THIS SQUARE FROM BELLOW
                                  ! BEFORE IT REACHES THE SIDE OR THE END OF THE RAY.
2     Y4=RFFM*X4+RFC              ! TO FIND THE Y COORDINATE ON THE SIDE WALL.
300   IF(Y4.LT.(IY+1))  GO TO 400 ! IF TRUE RAY PASSES OUT THE SIDE OF THE SQUARE OR STARTED WITHIN IT.
      Y4=IY+1                     ! FIND THE COORDINATES AT WHICH THE RAY LEAVES THE TOP OF THE SQUARE.
      X4=(Y4-RFC)/RFFM
      ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)             ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      Z1=(-9.8*LOG10(ALONG)+84.6)                  ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE ENTERING THIS SQUARE.
      ALONG=ALONG+ALNG                             ! LENGTH OF RAY ON LEAVING THIS SQUARE.
      Z2=(-9.8*LOG10(ALONG)+84.6)                  ! TO FIND THE ABSORBED ENERGY OF THE RAY ON LEAVING THIS SQUARE.
           TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100   ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                        ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
      GO TO  500                                   !FIND THE NEXT SQUARE THROUGH WHICH THE RAY PASSESS.
400   ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)             ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      Z1=(-9.8*LOG10(ALONG)+84.6)                  ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE ENTERING THIS SQUARE.
      ALONG=ALONG+ALNG                             ! LENGTH OF RAY ON LEAVING THIS SQUARE.
      Z2=(-9.8*LOG10(ALONG)+84.6)                  ! TO FIND THE ABSORBED ENERGY OF THE RAY ON LEAVING THIS SQUARE.
           TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100   ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                        ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4                                        ! FIND THE ABSORBTION OF THE RAY IN THE NEXT SQUARE THROUGH
100   CONTINUE                                     ! WHICH THE RAY PASSES.
                                                             !UPDATE THE LENGTH OF THE RAY .
      RLOP=RLOP+SQRT((X1-X2)**2+(Y1-Y2)**2)
*     TYPE 98,RLOP
```

```
      IF (TRAP.EQ.0) TABLE(IXX2,IYY2)=TABLE(IXX2,IYY2)+0.001*Z2        !ABSORBTION DUE TO REFLECTANCE. (10% OF Z2%=0.001*Z2).
      IF (TRAP.EQ.0) RLOP=10**(0.8633+0.9*LOG10(RLOP))                 !APPARENT LENGTH OF RAY DUE TO REFLECTANCE.
*     TYPE 99,RLOP
      RETURN                                                           ! RETURN TO MAIN PROGRAM TO OBTAIN NEXT RAY.
```

```
C**   **DIRECTION OF RAY IS IN THE THIRD QUADRANT.**

3     X3=XX2                        ! TO RETAIN THE FINAL COORDINATES OF THIS RAY IE. (XX2,YY2).
      Y3=YY2                        ! AND FOR CONVENIANCE WE SHALL START IN THIS SQUARE AND WORK BACKWARDS
      DO 10000 NNNN=IXX2,IXX1       ! A LOOP. TO ENTER THE RESULTS OF THE ENERGY ABSORBTION OF THE RAY
                                    ! IN EACH SQUARE INTO THE TABLE OF RESULTS.
50000 IX=INT(X3)                           ! THE COORDINATES OF THE SQUARE IN WHICH THE RAY FINISHES.
      IY=Y3
      X4=IX+1                       ! LAST X COORDINATE IN THIS SQUARE AND FIRST X COORDINATE OF THE NEXT
                                    ! SQUARE IF THE RAY PASSES OUT OF THE SIDE OF THE SQUARE.
      IF(X4.LT.XX1)  GO TO  20000   ! TO TEST WETHER THE RAY STOPS SHORT OF THIS COORDINATE OR NOT.
      X4=XX1                        ! TO FIND THE RAY LENGTH IN THIS THE LAST SQUARE USE THE RAYS STARTING
      Y4=YY1                        !COORDINATES.
      GO TO  30000                  ! TEST TO SEE IF THE RAY PASSES INTO THIS SQUARE FROM THE TOP
                                    ! OR STARTS IN THIS SQUARE.
20000 Y4=RFFM*X4+RFC                ! TO FIND THE Y COORDINATE ON THE SIDE WALL.
30000 IF(Y4.LT.(IY+1))  GO TO 40000 ! IF TRUE RAY PASSES OUT THE SIDE OF THE SQUARE OR STARTED WITHIN IT.
      Y4=IY+1                       ! FIND THE COORDINATES WHERE THE RAY ENTERS THE TOP OF THE SQUARE.
      X4=(Y4-RFC)/RFFM
      ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)            ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      ALOR=SQRT((X3-XX1)**2+(Y3-YY1)**2)          ! LENGTH OF RAY FROM THE STARTING POINT TO THE SQUARE LEAVING POINT.
      ALEN=ALONG+ALOR                             ! THE LENGTH OF THE ABSORBED RAY AT THE SQUARE LEAVING POINT.
      Z2=(-9.8*LOG10(ALEN)+84.6)                  ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE LEAVING THIS SQUARE.
      ALIR=ALEN-ALNG                              ! LENGTH OF RAY ON ENTERING THIS SQUARE.
      Z1=(-9.8*LOG10(ALIR)+84.6)                  ! TO FIND THE ABSORBED ENERGY OF THE RAY ON ENTERING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100 ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                       ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
      GO TO  50000                                !FIND THE NEXT SQUARE THROUGH WHICH THE RAY PASSES.
40000 ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)            ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      ALOR=SQRT((X3-XX1)**2+(Y3-YY1)**2)          ! LENGTH OF RAY FROM THE STARTING POINT TO THE SQUARE LEAVING POINT.
      ALEN=ALONG+ALOR                             ! THE LENGTH OF THE ABSORBED RAY AT THE SQUARE LEAVING POINT.
      Z2=(-9.8*LOG10(ALEN)+84.6)                  ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE LEAVING THIS SQUARE.
      ALIR=ALEN-ALNG                              ! LENGTH OF RAY ON ENTERING THIS SQUARE.
      Z1=(-9.8*LOG10(ALIR)+84.6)                  ! TO FIND THE ABSORBED ENERGY OF THE RAY ON ENTERING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100 ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                       ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
10000 CONTINUE                                    ! FIND THE ABSORBTION OF THE RAY IN THE NEXT SQUARE THROUGH
                                                  ! WHICH THE RAY PASSES.
                                                            !UPDATE THE LENGTH OF THE RAY .
      RLOP=RLOP+SQRT((X1-X2)**2+(Y1-Y2)**2)
*     TYPE 98,RLOP                                                !ABSORBTION DUE TO REFLECTANCE. (10% OF Z2%=0.001*Z2).
      IF (TRAP.EQ.0) TABLE(IXX2,IYY2)=TABLE(IXX2,IYY2)+0.001*Z2   !APPARENT LENGTH OF RAY DUE TO REFLECTANCE.
      IF (TRAP.EQ.0) RLOP=10**(0.8633+0.9*LOG10(RLOP))
```

```
*       TYPE 99,RLOP
        RETURN                                          ! RETURN TO MAIN PROGRAM TO OBTAIN NEXT RAY.


*98     FORMAT('RLOP BEFORE=',F8.4)
*99     FORMAT('RLOP  AFTER=',F8.4)
        END
```

```
*
*PROGRAM:       TABCNT.FOR
*WRITTEN BY:    R.W.ELLIOTT.

        SUBROUTINE  TABCNT      (TABTOT,TABLE,TOTENY,TENEGY,ANSWER,L)
        DIMENSION  TABLE(20,15),TABTOT(20,15),ANSWER(13,8)
        DO 10 N=1,15
        DO 20 M=1,18
        TABLE(M,N)=TABLE(M,N)/ANSWER(L,2)*100
        TABTOT(M,N)=TABTOT(M,N)+TABLE(M,N)
        TABLE(20,N)=TABLE(20,N)+TABLE(M,N)
        TOTENY=TOTENY+TABLE(M,N)
 20     CONTINUE
        TABTOT(20,N)=TABTOT(20,N)+TABLE(20,N)
 10     CONTINUE
        TENEGY=TENEGY+TOTENY
        RETURN
        END
```

```
*
*PROGRAMM:     TRAP2.FOR
*WRITTEN BY:    R...W.ELLIOTT.

        SUBROUTINE      TRAP2(X2,Y2,RLOP,COL)                 !COORDINATES AND LENGTH OF RAY ON ENTERING THE COLLECTOR.
        DIMENSION       COL(20),COLP(20)                              !CREATE TWO ONE  DIMENSIONAL ARRAYS.
        IX=INT(X2+10)                                         !RIGHT SHIFT FOR USE WITH ARRAYS.
        COL(IX)=COL(IX)+((84.6-9.8*LOG10(RLOP))/100)          !ENERGY REACHING THE COLLECTOR.
        RETURN                                                !RETURN TO MAIN PROGRAM.
        END
```

```
*
*PROGRAM        :RWE11T.FOR
*WRITTEN BY     :R.W.ELLIOTT.

      DOUBLE PRECISION  A,B,C,G,F,X,Y,X1,X2,Y1,Y2,YT,XI,XX,CK,Z        !THESE VARIABLES USE VERY HIGH ACCURACY SO AS TO
      DOUBLE PRECISION  DIS,R2,RT,RI,RR,RAY,FNQ,FSNQ,RFFM,RFFC         !OVERCOME THE PROBLEM OF RAYS WHICH PASS NEAR
      DOUBLE PRECISION  COSD,ASIN,SIND,DATAN,DSQRT,DABS,RAYR,DSIN,DCOS          !BOUNDARIES OR BOUNDARY INTERCEPTS.
      DIMENSION ANSWER(13,8),TABLE(20,30),TABTOT(20,30)        !CREATE TWO 3 DIMENSIONAL ARRAYS  WHICH ARE 13X8 AND 20X15.
      DIMENSION         COL(20),COLP(20),COLPT(20)        !CREATE THREE ONE DIMENSIONAL ARRAYS.
      INTEGER*4         D,TT,J,I,JT,IX
      OPEN(UNIT=32,NAME='ENERGY_TEMPT.DAT',TYPE='UNKNOWN')
      U=1.526                                             !THE REFRACTIVE INDEX OF THE 'HYPO 2000'.
      N=1
      S=0                                        !S IS A PARAMETER FOR LATERAL MOVEMENT OF THE SIDE SURFACES.
      L=0                                        !L IS A PARAMETER FOR CHANGING THE ANGLE OF THE LIGHT RAYS.
      P=1000000                                        !ANY RAY LONGER THAN 10 METERS IS IGNORED (HARDLY ANY).
      DO 100 IT=9,9                              !A LOOP TO CHANGE THE RADIOUS OF THE TOP SURFACE.
      R1=5*2**IT-10                              ! -F IS THE CENTRE OF THE TOP SURFACE.
                                                 !R1 IS THE RADIOUS OF THE TOP SURFACE.
      DO 200 IS=4,4                              !A LOOP TO CHANGE THE RADIOUS OF THE SIDE REFLECTING SURFACE
      G=6-4*2**IS                                !G IS A PARAMETER FOR THE SIDE REFLECTING SURFACES.
      DO 700 IH=15,15                            !A LOOP TO REDUCE THE HEIGTH, WITHOUT CHANGING THE RADIOUS.
      H=IH                                       !THE Y AXIS INTERCEPT OF THE TOP SURFACE.
      F=R1-H                                     !ADJUSTMENT OF F WHEN TOP SURFACE IS LOWERED.
      FF=(-F)                                    !THE Y COORDINATE OF THE CENTRE OF THE TOP SURFACE.
      DO  600  S=1,1                             !A LOOP TO MOVE OUT THE SIDES WITHOUT CHANGING THE RADIOUS.
                                                 !PARAMETER FOR CHANGING THE SIDES CENTRE WITH SAME RADIOUS.
      R2=DABS(G)                                 ! R2 IS THE RADIOUS OF THE SIDE SURFACES.
      GG=R2+S                                    ! X COORDINATES OF THE CENTRES OF THE TWO SIDE REFLECTING
      GGG=(-GG)                                  ! SURFACES.
      IF(DABS(F).LE.0.0001)  GO TO  700          !IF THE CENTRE OF THE TOP IS ON X AXIS EQUATIONS ARE UNTRUE.
      CK=(H**2+2*F*H-S*(2*G-S))/(2*F)            !THE CONSTANTS IN THE QUADRATIC EQUATION THAT WILL EVALUATE
      A=1+(G-S)**2/F**2                          !THE INTERCEPT BETWEEN THE SIDE SURFACES AND THE TOP SURFACE
      B=2*(G-S)*(CK+F)/F
      C=CK**2+2*F*CK-H**2-2*F*H
      IF(B**2-4*A*C)200,2,2                      !IF THE DISCRIMINANT IS NEGATIVE THEN NO INTERCEPT.
2     CALL QUADRT ( A,B,C,X)                     !SUBROUTINE TO EVALUATE A QUADRATIC ; AND GIVE +VE ROOT.
      IF(F.GT.0)  X=(-B-DSQRT(B**2-4*A*C))/(2*A) !IF CENTRE OF TOP SURFACE IS NEGATIVE WE NEED OTHER ROOT.
      Y=(G-S)*X/F+CK                             ! Y COORDINATE OF THIS INTERCEPT.
      IXQ=X/2                                    !CONDITION THAT CONCENTRATION IS > A FACTOR OF TWO.
      IF(IXQ.LT.S)  GO TO 700                    !IF SIDES ARE TO FAR APART CHANGE THE SHAPE.
      TYPE78                                     !PRINT OUT OF THE REFERENCES AND COORDINATES OF THIS SHAPE
      TYPE79,FF                                  !IE. THE CENTRES, RADII AND INTERCEPTS.
      TYPE80
      TYPE81,GGG,GG
      TYPE 50,R1
      TYPE 51, R2
      TYPE 52
      X=(-X)
      TYPE53 , X , Y
      X=(-X)
      TYPE 54, X , Y
      TYPE 56
      TYPE 57
      TYPE 58
      TYPE 59
      TYPE 69
      TYPE 60
      TYPE70                                     !THIS LOOP DETERMINES THE WIDTH OF THE COLLECTOR PLATE.
      DO 310 IQ=1,IXQ,1                          !Q IS THE RIGHT HAND X COORDINATE OF THE COLLECTOR PLATE.
      Q=IQ                                       !TEST IF COLLECTOR WIDTH IS < DISTANCE BETWEEN SIDES.
      IF(Q.LT.S)  GO TO  310                     ! QQ IS THE LEFT HAND X COORDINATE OF THE COLLECTOR.
      QQ=(-Q)
      YT=(S*(2*G-S)-2*(G-S)*Q-Q**2)              !THE Y COORDINATE OF THE COLLECTOR PLATE.
      YT=DSQRT(YT)                               ! ZQ IS THE WIDTH OF THE COLLECTOR.
      ZQ=Q-QQ
```

```
      TYPE75                                  !PRINT THE REFERENCES FOR THE COLLECTOR.
      TYPE76,Q,QQ
      TYPE 61
      TYPE 71
      CALL VOLUME (R1,R2,X,Y,Q,YT,F,S,VOL)    !SUBROUTINE TO OBTAIN THE INTERNAL VOLUME OF THE COLLECTOR.
      L=0                                     !L IS A PARAMETER FOR THE DIFFERENT INCIDENCE RAYS.
      TENEGY=0                                !A VARIABLE TO CALCULATE THE ENERGY ABSORBED IN THE COLLECTOR.
      DO 40 I=1,20
      COLPT(I)=0
40    CONTINUE
      DO 1000 I=1,30                          !A LOOP TO CREATE AN EMPTY ARRAY.
      DO 1100 J=1,20
      TABTOT(J,I)=0
1100  CONTINUE
1000  CONTINUE
      DO 300 LQ=240,300,5                     ! TO CHANGE THE ANGLE AT WHICH THE RAYS ENTER THE COLLECTOR.
      DO 800 I=1,20
      COL(I)=0
      COLP(I)=0
      DO 900 J=1,30
      TABLE(I,J)=0
900   CONTINUE
800   CONTINUE
      REF=0                                   !REF IS THE NUMBER OF REFLECTIONS. AT START SET TO ZERO.
      TOTENY=0
      IX=99*X                                 !RANGE OF INCIDENCE RAYS ON THE TOP SURFACE MAGNIFIED BY 99.
      XZ=0.9999*X                             !CONDITION : COORDINATE FOR LIMIT OF  BOUNDARY ACCURACY.
      L=L+1                                   !FIRST VALUE OF L FOR FIRST CONSIDERED INCIDENCE ANGLE.
      ANSWER(L,1)= LQ                         !ANGLE OF INCIDENCE FOR EACH  VALUE OF L.
      ANSWER(L,2) = 0                         !NUMBER OF RAYS INCIDENT ON TOP SURFACE BEING CONSIDERED.
      ANSWER(L,3) = 0                         !NUMBER OF SIDE REFLECTIONS FOR THIS SHAPE AT THIS ANGLE.
      ANSWER(L,4) = 0                         !NUMBER OF TOTAL INTERNAL REFLECTIONS FOR THIS SHAPE AT THIS ANGLE.
      ANSWER(L,5) = 0                         !THE FRACTION OF INCIDENT ENERGY REACHING COLLECTOR AT THIS ANGLE.
      ANSWER(L,6) = 0                         !NUMBER OF RAYS REACHING THE COLLECTOR AFTER ABSORBTION LOSES.
      ANSWER(L,7) = 0                         !NUMBER OF RAYS INCIDENT REACHING THE COLLECTOR.
      ANSWER(L,8)=0                           !FRACTION OF INCIDENT RAYS REACHING THE COLLECTOR AT THIS ANGLE.
      DO 455 IXI=IX,(-IX),-1                  !A LOOP TO CONSIDER EACH RAY, LEAVING 1% OF WIDTH AT BOUNDARIES.
*     TYPE*,IXI
      XI=IXI                                  ! X COORDINATE OF INCIDENT RAY MAGNIFIED BY 100 TIMES.
      X1=XI/100                               ! X COORDINATE OF THE INCIDENT RAY. EACH RAY 1/100TH OF A CM APART.
      TRR=90                                  ! PARAMETER FOR TOTALLY INTERNALLY REFLECTED RAY. PRESET TO
                                              ! LARGE VALUE SO AS THIS CONDITION WILL NOT EJECT RAY UNLESS RESET
                                              ! BY TOTAL INTERNAL REFLECTING CONDITION.
      TIR=0                                   ! COUNTS THE NUMBER OF TIMES RAY TOTALLY INTERNALLY REFLECTED.
      TRAP=0                                  !CONDITION. IF TRAP=0 THEN RAY HAS NOT REACHED THE COLLECTOR.
      RLOP=0.1                                !ASSUME 5.6% ABSORPTION IN FIRST 1MM. REFLECTION LOSSES TO BE ADDED.
      REF=0                                   !RESET NO OF REFLECTIONS TO ZERO FOR NEW RAY.
******************************************
*     RAY STARTING FROM TOP SURFACE     *
******************************************
      JT=4                                    !IF JT=4 THEN 'TAB' WILL ADD 3% TO FIRST SQUARE OF ABSORPTION MESH.
      J=4                                     !IF J=4 THEN RAY IS ENTERING THE TOP SURFACE.
      D=1                                     !IF D=1 THEN RAY IS COMING FROM TOP SURFACE AND RAY MUST BE TESTED
                                              !FOR INTERCEPTION ON SIDE SURFACES BEFORE TESTING AT THE COLLECTOR.
                                              !PARAMETERS OF THE EQUATION FOR THE Y VALUE OF THE INCOMING RAY.
      A=1
      B=2*F
      C=X1**2-H**2-2*F*H
1     CALL QUADRT (A,B,C,Y1)                  !Y1 IS THE Y COORDINATE OF THE STARTING POINT OF THE RAY.
      IF(X1.EQ.0) THEN                        !AT THIS POINT THE NORMAL 'FNQ' IS VERTICAL THEREFORE SET FNQ=90°
            FNQ=90                            !SET THE NORMAL OF THE TOP SURFACE TO 90°.
      ELSE                                    !RETURN TO PROGRAM TO CALCULATE THE REFRACTED RAYS ANGLE (RAY).
            FNQ=DATAN((Y1+F)/X1)              !THE NORMAL TO THE TOP SURFACE IN RADIANS ANTICLOCKWISE FROM X AXIS.
            FNQ=FNQ*180/3.141592653589793238  !THE NORMAL TO THE TOP SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS.
            IF(FNQ.LT.0)  FNQ=FNQ+180
      ENDIF
3     I=LQ-180                                !I IS A PARAMETER FOR THE INCIDENT RAY.
```

```
      IF(I.LE.FNQ)  RI=FNQ-I                        !RI IS THE ANGLE OF INCIDENCE FOR THE INCOMING RAY.
      IF(I.GT.FNQ)  RI=I-FNQ
      IF(RI.GE.90)  GO TO  450                  !IF THE INCIDENCE ANGLE IS GREATER THAN 90' THEN COORDINATE IS IN SHADOW.
      RR=ASIN(SIND(RI)/U)                                  !REFRACTED ANGLE IN RADIANS.
      RR=RR*180/3.141592653589793238                       !REFRACTED ANGLE IN DEGREES.
      IF(I.LE.FNQ)  RAY=FNQ-RR+180                         !RAY IS THE ANGLE THE LIGHT BEAM MAKES WITH THE X AXIS.
      IF(I.GT.FNQ)  RAY=FNQ+RR+180
      IF((RAY.EQ.90).OR.(RAY.EQ.270))  X2=X1               !IF RAY IS VERTICAL ITS SLOPE IS INFINITE SO PUT X2=X1.
                                                           !IF RAY IS VERTICAL PUT X2=X1 AND FIND THE Y INTERCEPT.
      RN=RR-RI                                                    !THE DIFFERENCE BETWEEN THE INCIDENT AND REFRACTED ANGLES.
      RP=RR+RI                                                    !THE ADDITION OF THE INCIDENT AND REFRACTED ANGLES.
      IF(RN.LE.0.1)   THEN
            R=((U-1)/(U+1))**2
      ELSE
            R=1/2*(((SIND(RN))**2/(SIND(RP))**2)+((TAND(RN))**2/(TAND(RP))**2)) !THE REFLECTANCE ON THE TOP SURFACE.FRESNELL RELA
TIONSHIP.
      ENDIF
      RLOP=(10**((84.6+R*100-94.4)/9.8))                   !THE APPARENT LENGTH OF THE RAY DUE TO REFLECTION ON THE TOP SURFACE.
      IF(RAY.EQ.90)  GO TO  12                             !IF RAY+90 ONLY INTERCEPT IS WITH THE TOP SURFACE.
      IF(RAY.EQ.270)  GO TO  17                            !IF RAY=270 THEN RAY CAN ONLY BE COMING FROM THE TOP SURFACE,M
*********************************
*     RAY STARTING TREK        *
*********************************
3?    RAYR=RAY*3.141592653589793238/180
      RFFM=DSIN(RAYR)/DCOS(RAYR)                     !FIND THE SLOPE OF THE RAY  (RFFM).
      RFFC=Y1-X1*DSIN(RAYR)/DCOS(RAYR)               !FIND THE INTERCEPT OF THE RAY  (RFFC).
      IF((RAY.LT.90).AND.(J.EQ.2))  GO TO  88        !IF J=2 THEN RAY IS COMING FROM R.H.S. AND WITH RAY < 90'IT CAN ONLY
                                                     !INTERCEPT WITH THE TOP SURFACE.
      IF((TT.EQ.1).AND.(D.EQ.0))  GO TO  9           !D=0 MEANS THE RAY MUST BE COMING FROM THE SIDE SURFACES. TT=1 MEANS
                                                     !RAY < 180' THEREFORE IMPOSSIBLE INTERCEPT WITH COLLECTOR.
      IF(D.EQ.1)  GO TO  21                          !TEST THE SIDE SURFACES BEFORE THE COLLECTOR FOR RAY INTERSECTION
****************************************                  !BECAUSE RAY IS COMING FROM  THE TOP SURFACE.
*     RAY INTERCEPT WITH COLLECTOR     *
****************************************
19    X2=(-RFFC/RFFM)                                !X2 IS THE RAY INTERCEPT ON THE X AXIS.
17    IF((DABS(X2)-S).LE.0.0001)  THEN               !THE RAY ENTERS THE COLLECTOR.
            Y2=YT                                          !FIND THE Y COORDINATE OF THE RAY ON THE COLLECTOR SURFACE.
            IF(X2.GT.S) THEN                         !IF THE NEW X COORDINATE IS OUTSIDE THE COLLECTOR RANGE.
                  X2=S-0.0001
                                                     !USE ITS LIMITING VALUES.
            ELSE
                  IF (X2.LT.(-S)) THEN
                        X2=0.0001-S
                  ENDIF
            ENDIF
            TRAP=1                                         !TRAP=1 IS THE VARIABLE TO SHOW THE RAY HAS REACHED THE COLLECTOR.
            GO TO  14                                      !NOW FIND THE TOTAL LENGTH OF THE RAY IN THE LIQUID.
      ENDIF
      X2=X1                                          !REPLACE X2 WITH ORIGINAL VALUE SINCE THIS VALUE IS INCORRECT.
      D=0
 9    IF(J.EQ.1)  GO TO  44                          !RAY COMING FROM L.H.S. THEREFORE TEST FOR INTERCEPT ON R.H.S.
*********************************
*     INTERCEPT L.H.S.         *
*********************************
                                                     !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
      A=1+RFFM**2                                    !THE L.H.S.  (LEFT HAND SIDE SURFACE).
      B=2*RFFM*RFFC-2*(G-S)
      C=RFFC**2-2*(G-S)*S-S**2                             !NO INTERCEPT ON L.H.S. AND RAY COMING FROM TOP SURFACE ON L.H.S.
      IF((B**2.LT.4*A*C).AND.(D.EQ.1))  GO TO  19    !SO TRY COLLECTOR AND SET PARAMETER  D TO ZERO. TEST COMPLETE.
                                                     !NO INTERCEPT ON L.H.S. SO TRY R.H.S.  (RIGHT HAND SIDE SURFACE).
      IF(B**2.LT.4*A*C)  GO TO  44                   !SUBROUTINE TO FIND THE LARGEST ROOT OF A QUADRATIC.
      CALL QUADRT (A,B,C,X2)
      IF((RFFM.LT.0).AND.(J.GE.3)) CALL QUADNG(A,B,C,X2)!WITH AN INTERCEPTION ON THE L.H.S. AND RAY -VE FIND THE LEAST ROOT.
                                                           !IF SLOPE IS -VE AND INTERCEPT IS NOT ON R.H.S. FIOND SMALLEST ROOT.
                                                           !RAY INTERCEPT WITH L.H.S. OUTSIDE BOUNDARY CONDITIONS.
      IF((X2.LT.-X).AND.(D.EQ.1))  THEN                    !D=0 MEANS SIDE SURFACES HAVE BEEN TESTED FOR INTERCEPTION OF RAY.
            D=0                                            !PRIOR TO IT BEING TESTED AT THE COLLECTOR.
                                                           !THE RAY CAN NOW BE TESTED FOR INTERCEPT WITH COLLECTOR.
            GO TO 19
```

```
      ENDIF
      IF(X2.LT.-X)  THEN                               !INTERCEPT WITH L.H.S. OUTSIDE BOUNDARY CONDITIONS. TRY R.H.S.S.
            X2=X1                                      !REPLACE NEW COORDINATE WITH OLD VALUE SINCE IT IS NOT VALID.
            GO TO 44                                   !INTERCEPT WITH L.H.S. OUTSIDE BOUNDARY CONDITION .TRY R.H.S.S.
      ENDIF
      J=1                                              !RAY HAS LIGITIMATE INTERCEPTION WITH L.H.S.
      D=0                                              !DO NOT TEST SIDE SURFACES BEFORE THE COLLECTOR. OR TEST COMPLETED.
      GO TO  66                                        !FIND Y COORDINATE  AND UP DATE RESULTS THEN FIND NEXT REFLECTION.
**********************************                     !SO TEST THE COLLECTOR FOR NEXT INTERCEPTION THEN R.H.S AND L.H.S.
*     RAY FROM TOP SURFACE    *
**********************************
21    IF(X1.LT.0)  GO TO  9                            !IF THE RAY IS COMING FROM THE L.H.S.TOP SURFACE  THEN TEST
                                                       !INTERCEPT WITH L.H.S. SURFACE BEFORE R.H.S. SURFACE.
44    IF((RAY.GE.90).AND.(RAY.LE.180))  GO TO  88      !IF 90<RAY<180 THEN RAY CAN NOT POSSIBLY INTERCEPT WITH R.H.S.
                                                       !THEREFORE TEST INTERCEPT WITH TOP SURFACE.
      IF(J.EQ.2)  GO TO  88                            !RAY COMING FROM R.H.S.  TEST NEXT INTERCEPTIWITH WITH TOP SURFACE.
**********************************
*     INTERCEPT R.H.S.        *
**********************************
      A=1+RFFM**2                                      !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
      B=2*RFFM*RFFC+2*(G-S)                            !THE R.H.S.    (RIGHT HAND SIDE SURFACE).
      C=RFFC**2-S*(2*G-S)
      IF((B**2.LT.4*A*C).AND.(D.EQ.1))  GO TO  19      !TEST SHOWS THAT WHEN RAY IS COMING FROM THE RIGHT HAND TOP SURFACE
                                                       !THERE IS NO INTERCEPTION WITH THE R.H.S. SURFACE. SO NOW
                                                       !TEST INTERCEPTION WITH COLLECTOR AND SET D=0 TO SHOW TEST COMPLETE.
      IF(B**2.LT.4*A*C)  GO TO 88                      !NO INTERCEPT WITH R.H.S.  NEXT TEST INTERCEPTION WITH TOP SURFACE.
      CALL QUADRT (A,B,C,X2)                           !INTERCEPTION WITH R.H.S. SO CALCULATE X COORDINATE.
      IF(X2.GT.X1) CALL QUADNG(A,B,C,X2)               !IF RAY IS IN FOURTH QUADRANT THE SMALLEST INTERCEPT IS REQUIRED.
      IF((X2.GT.X).AND.(D.EQ.1))  GO TO  19            !INTERCEPT OUTSIDE THE SHAPE .TEST COMPLETE. NEXT TEST COLLECTOR.
      IF(X2.GT.X)  GO TO  88                           !INTERCEPT OUTSIDE THE SHAPE. SO NEXT TEST TOP SURFACE.
      J=2                                              !RAY HAS LIGITIMATE INTERCEPTION WITH R.H.S.
      D=0                                              !DO NOT TEST SIDE SURFACES BEFORE THE COLLECTOR; OR TEST COMPLETED.

**************************************************
*     FIND THE Y COORD. EITHER L. OR R.          *
**************************************************

66    IF(J.EQ.1)  THEN                                 !FIND Y COORDINATE FOR THE L.H.S. SURFACE INTERCEPT.
93          Y2=DSQRT(S**2+2*(G-S)*S+2*(G-S)*X2-X2**2)  !THE Y COORDINATE FOR THE L.H.S. SURFACE INTERCEPT.
      ELSE
            Y2=DSQRT(S*(2*G-S)-2*(G-S)*X2-X2**2)       !THE Y COORDINATE FOR THE R.H.S. SURFACE INTERCEPT.
      ENDIF
      IF ((J.LE.2).AND.((DABS(X2)-Q).LE.0.0001)) THEN  !TEST TO SEE IF INTERCEPT IS WITHIN THE COLLECTOR.
            Y2=YT                                      !FIND THE Y COORDINATE OF THE RAY ON THE COLLECTOR SURFACE.
            X2=(Y2-RFFC)/RFFM                          !FIND THE Y COORDINATE OF THE RAY FOR THIS VALUE OF Y.
            IF(X2.GT.Q)      THEN
                  X2=Q-0.0001                          !IF THE NEW X COORDINATE IS OUTSIDE THE COLLECTOR RANGE.
            ELSE
                  IF (X2.LT.QQ) THEN
                        X2=QQ+0.0001                           !USE ITS LIMITING VALUES.
                  ENDIF
            ENDIF
            TRAP=1                                     !TRAP=1 IS THE VARIABLE TO SHOW THE RAY HAS REACHED THE COLLECTOR.
            GO TO  14                                  !FIND THE TOTAL LENGTH OF THE RAY IN THE LIQUID BEFORE IT REACHES
      ENDIF                                            !                                                  THE COLLECTOR.
96    REF=REF+1                                        !ADD ONE TO THE NUMBER OF SIDE REFLECTIONS.
      CALL  TABT(J,X1,Y1,X2,Y2,RFFM,RFFC,RLOP,TABLE,TRAP)  !INTERCEPT WITH SIDE SURFACE.
      IF(RLOP.GT.P)  GO TO 450                         !IF RAY IS TOO LONG ITS BEEN MOSTLY ABSORBED SO NEGLECT REMAINDER.
      IF((X2.GT.XZ).OR.(X2.LT.-XZ))  GO TO  450        !IF RAY PASSES OUTSIDE THESE LIMITS ASSUME RAY HAS ESCAPED.
      IF(X2.LT.0)  THEN
            XX=Y2/(X2-(G-S))                           !FIND THE NORMAL OF THE L.H.S. SURFACE AT THE POINT OF INTERCEPTION.
      ELSE
            XX=Y2/(X2-(S-G))                           !FIND THE NORMAL OF THE R.H.S. SURFACE AT THE POINT OF INTERCEPTION.
      ENDIF
      FSNQ=DATAN(XX)                                   !THE NORMAL TO THE SIDE SURFACE IN RADIANS ANTICLOCKWISE FROM X AXIS
      FSNQ=FSNQ*180/3.141592653589793238               !THE NORMAL TO THE SIDE SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS
```

```
      IF((FSNQ.LT.180).AND.(FSNQ.GT.0))  GO TO  4           !IF NORMAL IN CORRECT QUADRANTS FIND THE REFLECTED RAY.
      FSNQ=FSNQ+180                                          !CORRECT THE NORMAL FOR INCORRECT QUADRANTS.
4     IF(J.EQ.2)  THEN                                       !IF THE INTERCEPT IS ON THE R.H.S. SURFACE FIND ITS REFLECTED RAY.
            CALL  RAYJ2(RAY,FSNQ,TT)                         !FIND THE REFLECTED RAY ANGLE FOR R.H.S SURFACE AND SET TT.
      ELSE
            CALL  RAYJ1(RAY,FSNQ,TT)                         !FIND REFLECTED RAY ANGLE FOR L.H.S. SURFACE AND SET PARAMETER TT.
      ENDIF                                                  !SET THE DIRECTION PARAMETER TT=1 FOR ALL RAY TRAVELLING UPWARDS.
      X1=X2                                                  !THE FINAL COORDINATES OF THE OLD RAY BECOME THE START COORDINATES
      Y1=Y2                                                  !OF THE NEW RAY.
      GO TO  33                                              !FIND THE SLOPE OF THE NEW RAY AND FIND THE NEXT INTERCEPT.
25    X1=X2                                                  !THE FINAL COORDINATES OF THE OLD RAY BECOMES THE INITIAL
      Y1=Y2                                                  !COORDINATES OF THE NEW RAY.
      RAYR=RAY*3.141592653589793238/180
      RFFM=DSIN(RAYR)/DCOS(RAYR)                             !FIND THE SLOPE OF THE RAY  (RFFM).
      RFFC=Y1-X1*DSIN(RAYR)/DCOS(RAYR)                       !FIND THE INTERCEPT OF THE RAY  (RFFC).

*****************************************
*     INTERCEPT WITH TOP SURFACE        *
*****************************************

88    A=1+RFFM**2                                            !THE PARAMETERS OF THE EQUATION FOR THE INTERCEPT OF THE RAY WITH
      B=2*F*RFFM+2*RFFM*RFFC                                 !THE TOP SURFACE.
      C=RFFC**2-H**2-2*F*H+2*F*RFFC
      IF(RFFM.LT.0) THEN                                     !IF THE SLOPE OF THE RAY IS -VE THEN THE SMALLEST ROOT IS REQUIRED.
            CALL QUADNG (A,B,C,X2)                           !IF SLOPE OF RAY IS -VE THEN THE SMALLEST ROOT IS REQUIRED.
            IF((J.GE.3).AND.(DABS(X2-X1).LE.0.0001))  CALL QUADRT(A,B,C,X2) !POSSIBLE EXCEPTIONS WHEN LARGEST ROOT IS REQUIRED.
      ELSE
            CALL QUADRT (A,B,C,X2)                           !SUBROUTINE TO FIND THE LARGEST ROOT OF A QUADRATIC EQUATION.
            IF((J.GE.3).AND.(DABS(X2-X1).LE.0.0001))  CALL QUADNG(A,B,C,X2) !IF RAY STARTS ON THE TOP SURFACE MAKE SURE THE
                                                             !START COORDINATES ARE NOT THE SAME AS THE FINISH.
      ENDIF
      IF((X2.GT.X).OR.(X2.LT.(-X)))  GO TO  33               !IF INTERCEPT NOT WITHIN THE SHAPE THEN TRY A SIDE SURFACE.
12    A=1                                                    !THE PARAMETERS OF THE QUADRATIC EQUATION TO FIND THE Y COORDINATE
      B=2*F                                                  !OF THE INTERCEPT WITH THE TOP SURFACE.
      C=X2**2-H**2-2*F*H
      CALL  QUADRT (A,B,C,Y2)                                !SUBROUTINE TO FIND THE LARGEST VALUE OF A QUADRATIC EQUATION.
      IF (X2.GT.XZ.OR.X2.LT.-XZ) GO TO 14                    !IF RAY PASSES OUTSIDE THESE LIMITS ASSUME RAY HAS ESCAPED.
      IF(Y2.LT.Y)  GO TO  33                                 !IF NEW INTERCEPT IS OUTSIDE THE SHAPE THEN TRY A SIDE SURFACE.
      IF(DABS(Y2-RFFM*X2-RFFC).GE.0.1) GO TO 33              !A TEST TO MAKE SURE THE COORDINATE FOUND ARE OF A POINT ON THE RAY.
      FNQ=DATAN((Y2+F)/X2)                                   !FIND THE NORMAL OF THE TOP SURFACE AT THE POINT OF INTERCEPTION.
      FNQ=FNQ*180/3.141592653589793238                       !THE NORMAL TO THE TOP SURFACE IN DEGREES ANTICLOCKWISE FROM X AXIS.
      IF(FNQ.LT.0)  FNQ=FNQ+180                              !MAKE THE NORMAL TO THE TOP SURFACE LIE IN THE 1ST OR 2ND QUADRANTS.
      RR=DABS(RAY-FNQ)                                       !THE REFLECTED RAY IS EQUAL TO THE INCIDENCE RAY.
      IF(RR.GT.180)  RR=360-RR                               !THE REFLECTED RAYS ANGLE MUST BE ACUTE.
      IF(RR.LT.40)  GO TO 63                                 !IF THE INCIDENCE ANGLE IS<40' THEN RAY IS NOT INTERNALLY REFLECTED.
      J=3
      D=1
      TIR=TIR+1
      CALL  TABT(J,X1,Y1,X2,Y2,RFFM,RFFC,RLOP,TABLE,TRAP)    !INTERCEPT ON TOP SURFACE WITH TOTAL INTERNAL REFLECTION.
      IF(RLOP.GT.P)  GO TO 450
      ANSWER(L,4)=( ANSWER(L,4)+1)
      IF((RAY.GT.FNQ).AND.(RAY.LT.270))  THEN
            RAY=FNQ-RR+180                                   !THE ANGLE OF TOTALLY INTERNALLY REFLECTED RAY ON THE TOP SURFACE.
      ELSE
            RAY=FNQ+RR+180
      ENDIF                                                  !CORRECT THE RAY TO BE IN BETWEEN 0' AND 360'.
      IF(RAY.GE.360)  RAY=RAY-360
      IF (RAY. LE.180.AND.RAY.GE.0) THEN
            TT=1
      ELSE
            TT=0
      ENDIF
      GO TO  25

*********************************
*     RAY HAS ESCAPED           *
```

```
*********************************

63      TRR=RR
14      CALL  TABT(J,X1,Y1,X2,Y2,RFFM,RFFC,RLOP,TABLE,TRAP)!ITERCEPT TOP OR BOTTOM.
        IF( RLOP.GT.P) GO TO 450
        IF(TRR.LT.40)  GO TO  450
        IF(TRAP.EQ.0)  GO TO  450
        CALL    TRAPZT(X2,Y2,RLOP,COL)                    !SUBROUTINE TO FIND THE DISTRIBUTION OF ENERGY AT THE COLLECTOR.
        ANSWER(L,6)=ANSWER(L,6)+((84.6-9.8*LOG10(RLOP))/100)    !FRACTION OF ENERGY REACHING COLLECTOR AT THIS ANGLE
                ANSWER(L,7)=ANSWER(L,7)+1                           !NO OF RAYS REACHING THE COLLECTOR AT THIS ANGLE.
450             ANSWER(L,2)=ANSWER(L,2)+1                       ! COUNTS NUMBER OF RAYS INCIDENT ON TOP SURFACE.
                ANSWER(L,3)=ANSWER(L,3)+REF                 ! COUNTS TOTAL NUMBER OF SIDE REFLECTIONS FOR EACH INCIDENCE ANGLE.
455             CONTINUE
                ANSWER(L,5)=ANSWER(L,6)/ANSWER(L,2)         !FRACTION OF INCIDENT ENERGY REACHING THE COLLECTOR AT THIS ANGLE.
                ANSWER(L,8)=ANSWER(L,7)/ANSWER(L,2)         !FRACTION OF INCIDENT RAYS REACHING THE COLLECTOR AT THIS ANGLE
                CALL TABCNIT (TABTOT,TABLE,TOTENY,TENEGY,ANSWER,L) !SUBROUTINE TO CALCULATE TOTAL ENERGY ABSORBED IN THIS SHAPE.
                TYPE 62,(ANSWER(L,J),J=1,8)
                DO 94 N=30,1,-1
                TYPE82,(TABLE(M,N),M=3,16),TABLE(20,N)
94              CONTINUE
                DO 101 I=1,19                               !LOOP TO FIND THIS ENERGY AS A PERCENTAGE.
                COLP(I)=COL(I)/ANSWER(L,2)*100              !ARRAY WITH ENERGY AS A PERCENTAGE.
                COLPT(I)=COLPT(I)+COLP(I)
                COLP(20)=COLP(20)+COLP(I)
101             CONTINUE
                COLPT(20)=COLPT(20)+COLP(20)
                TYPE82,(COLP(I),I=3,16),COLP(20)
                TYPE85,TOTENY
                TYPE86,COLP(20)                             !TOTENY IS THE PERCENTAGE OF INCOMING ENERGY ABSORBED IN THE LIQUID.
                TYPE87,(TOTENY+COLP(20))
******************************************
*       CREATE ENERGY GENERATION FILE   *
******************************************

                IF (LQ.GE.270) THEN                         !CHOOSE ANGLES OF INCIDENCE.
                        DO 194 N= 30,1,-1
                        WRITE(32,2000)  (TABLE(M,N),M=2,17)
194                     CONTINUE

                        WRITE(32,2000) (COLP(I),I=2,17)
                        WRITE(32,89) LQ,COLP(20)
                ENDIF

                CONTINUE
                CALL EFFY (ANSWER,R1,R2,FF,GG,X,YT,H,ZQ,VOL)
                DO 48 N=1,20
                COLPT(N)=COLPT(N)/L                         !CORRECT THE COLLECTOR ARRAY TO PERCENTAGES.
48              CONTINUE
                DO 98 N=1,30
                DO 99 M=1,20
                TABTOT(M,N)=TABTOT(M,N)/L                       !CORRECT THE TOTAL ENERGY IN THE COLLECTOR TO A PERCENTAGE.
99              CONTINUE
98              CONTINUE

                DO 97 N=30,1,-1
                TYPE82,(TABTOT(M,N),M=3,16),TABTOT(20,N)
97              CONTINUE
                TENEGY=TENEGY/L                             !CORRECT THE TOTAL ENERGY IN THE COLLECTOR TO A PERCENTAGE.
                TYPE82,(COLPT(I),I=3,16),COLPT(20)
                TYPE85,TENEGY
                TYPE86,COLPT(20)
                TYPE87,(TENEGY+COLPT(20))
310             CONTINUE
600             CONTINUE
700             CONTINUE
200             CONTINUE
```

```
100       CONTINUE
          GO TO 20
50        FORMAT (5X'LENGTH OF RADIUS OF TOP SURFACE',5X,F8.0)
51        FORMAT (5X'LENGTH OF RADIUS OF SIDE SURFACE',4X,F8.0)
52        FORMAT(5X'COORDINATES OF CURVED SURFACE INTERSECTION')
53        FORMAT(5X'( ',F6.2,' , ',F6.2,' )')
54        FORMAT('+'30X,'( ',F6.2,' , ',F6.2,' )')
56        FORMAT(5X'ANGLE OF RAY_______________________________LQ.')
57        FORMAT(5X'X COORDINATE OF INCOMING RAY_______________C.O.R.')
58        FORMAT(5X'NUMBER OF SIDE REFLECTIONS_________________N.O.S.R.')
59        FORMAT(5X'NUMBER OF TIMES BEAM TOTALLY INTERNALLY ')
69        FORMAT(5X,'REFLECTED ON  TOP SURFACE ________________T.I.R.')
60        FORMAT(5X'INTENSITY AS A PERCENTAGE O F INCIDENT RAYS')
70        FORMAT('+'48X,'_INTENSITY.')
61        FORMAT('-',' LQ.'5X'C.O.R.'5X'N.O.S.R.')
71        FORMAT('+'35X'T.I.R.'5X'RAY.ESC.'5X'INTENSITY.')
62        FORMAT(5X,/,8F10.3,/)
64        FORMAT('+'45X'ESCAPED.')
67        FORMAT('+'22X,F5.1)
68        FORMAT('+'65X,'TO LONG.')
72        FORMAT('+'45X,'COORDINATE IS IN SHADOW.')
73        FORMAT('+'32X,F6.1)
74        FORMAT('+'65X,F6.2)
7         FORMAT('0',' X  COORDINATES OF THE SOLAR TRAP')
76        FORMAT('+'35X,'ARE BETWEEN',F4.1,'  AND',F4.1)
78        FORMAT('-',' THE CENTRE OF THE  TOP CURVED ')
79        FORMAT('+'31X,'SURFACE IS ( O ,',F7.1,').')
80        FORMAT(' THE CENTRE OF THE SIDE CURVED SURFACE ARE ')
81        FORMAT('+'43X,'(',F5.1,' , O ) AND (',F5.1,' , O )')
82        FORMAT(5X,15F8.3)
85        FORMAT(5X'% ENERGY ABSORBED IN HYVIS '4X,F5.2)
86        FORMAT('+'45X,'% ENERGY REACHING RECEIVER',4X,F5.2)
87        FORMAT('+'80X,'% TOTAL ENERGY GAINED IN COLLECTOR',4X,F6.2)
89        FORMAT(5X,I3,5X,F5.2)
2000      FORMAT(2X,16F8.5)
20        END
```

```
*
*PROGRAM:      TABT.FOR
*WRITTEN BY:   R.W.ELLIOTT.

      SUBROUTINE        TABT (J,X1,Y1,X2,Y2,RFFM,RFFC,RLOP,TABLE,TRAP)
      DOUBLE PRECISION        X1,XX1,X2,XX2,Y1,YY1,Y2,YY2,X3,X4,Y3,Y4
      DOUBLE PRECISION        RFFM,RFFC,RFC,RLOP,ALONG,ALEN,ALNG,ALIR,ALOR
      DOUBLE PRECISION        SQRT,LOG10,Z1,Z2,Z
      INTEGER*4               IX,IY,IXX1,IXX2,IYY1,IYY2
      DIMENSION TABLE(20,30)          ! DIMENSIONS OF TABLE OF RESULTS.
      XX1=2*X1+10                     ! TO MAKE SHAPE HAVE POSITIVE COORDINATES FOR TABLE ARRAY
      XX2=2*X2+10                     ! CONVENIANCE.
      YY1=2*Y1+1                      ! TO ALLOW FOR ZERO COORDINATES TO FIT IN THE ARRAY.
      YY2=2*Y2+1                      ! TO ALLOW FOR ZERO COORDINATES TO FIT IN THE ARRAY.
      RFC=YY1-RFFM*XX1                ! TO GIVE THE RAY A LATERAL SHIFT OF TEN UNITS X1,X2 AND
                                      ! THE INTERCEPT HAVE TO BE CHANGED.
      IXX1=XX1                        ! TO FIND THE X COORDINATES OF THE ELEMENT IN WHICH THE RAY
      IYY1=YY1                        ! Y COORDS..
      IXX2=XX2                        ! STARTS AND FINISHES.
      IYY2=YY2                        ! Y COORDS..
      IF (ABS(IYY1-YY1).LE.0.0001) IYY1=IYY1-1        ! BORDER LINE CASE USE ELEMENT BELOW.
      IF (JT.EQ.4) THEN
            TABLE(IXX1,IYY1)=TABLE(IXX1,IYY1)+0.03    ! 3% ABSORBTION IN FIRST 1mm.
            JT=0
      ENDIF
      ALONG=RLOP                                      ! LENGTH OF RAY TO DATE.
      IF(XX1.LE.XX2.AND.YY1.LT.YY2)  GO TO  1         ! THESE STATMENTS ARE TO FIND IN WHICH WAY THE RAY IS GOING.
      IF(XX1.LE.XX2.AND.YY1.GT.YY2)  GO TO  4         ! SO AS TO CHOOSE THE CORRECT METHOD OF PLOTTING ITS PATH.
      IF(YY1.GE.YY2)  GO TO  3                        ! THIRD QUADRANT.




C**   **DIRECTION OF RAY IS IN THE SECOND QUADRANT.**

2     X3=XX2                          ! TO RETAIN THE FINAL COORDINATES OF THIS RAY IE. (XX2,YY2).
      Y3=YY2                          ! AND FOR CONVENIANCE WE SHALL START IN THIS SQUARE AND WORK BACKWARDS
      DO 10 N=IXX2,IXX1               ! A LOOP. TO ENTER THE RESULTS OF THE ENERGY ABSORBTION OF THE RAY
                                      ! IN EACH SQUARE INTO THE TABLE OF RESULTS.
50    IX=X3                           ! THE COORDINATES OF THE SQUARE IN WHICH THE RAY FINISHES.
      IY=Y3
      IF(Y3.EQ.IY)  IY=IY-1           ! IF THE COORDINATE IS ON THE LINE WE NEED THE SQUARE BELOW.
      X4=IX+1                         ! LAST X COORDINATE IN THIS SQUARE AND FIRST X COORDINATE OF THE NEXT
                                      ! SQUARE IF THE RAY PASSES OUT OF THE SIDE OF THE SQUARE.
      IF(X4.LT.XX1)  GO TO  20        ! TO TEST WETHER THE RAY STOPS SHORT OF THIS COORDINATE OR NOT.
      X4=XX1                          ! TO FIND THE RAY LENGTH IN THIS THE LAST SQUARE USE THE RAYS STARTING
      Y4=YY1                          !COORDINATES.
      GO TO  30                       ! TEST TO SEE IF THE RAY CAME INTO THIS SQUARE FROM BELLOW
                                      ! OR WETHER THE END OF THE RAY IS IN THIS SQUARE.
20    Y4=RFFM*X4+RFC                  ! TO FIND THE Y COORDINATE ON THE SIDE WALL.
30    IF(Y4.GE.IY)  GO TO 40          ! TEST IF RAY PASSES OUT THE SIDE OF THE SQUARE OR STARTED WITHIN IT.
      Y4=IY                           ! FIND THE COORDINATES AT WHICH THE RAY LEAVES THE BOTTOM OF SQUARE.
      X4=(Y4-RFC)/RFFM
      ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)/2.0            ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      ALOR=SQRT((X3-XX1)**2+(Y3-YY1)**2)/2.0          ! LENGTH OF RAY FROM THE STARTING POINT TO THE SQUARE LEAVING POINT.
      ALEN=ALONG+ALOR                                 ! THE LENGTH OF THE ABSORBED RAY AT THE SQUARE LEAVING POINT.
      Z2=(-9.8*LOG10(ALEN)+84.6)                      ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE LEAVING THIS SQUARE.
      ALIR=ALEN-ALNG                                  ! LENGTH OF RAY ON ENTERING THIS SQUARE.
      Z1=(-9.8*LOG10(ALIR)+84.6)                      ! TO FIND THE ABSORBED ENERGY OF THE RAY ON ENTERING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100     ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
```

```
      X3=X4                                          ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
      GO TO  50                                      !FIND THE NEXT SQUARE THROUGH WHICH THE RAY PASSES.

40    ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)/2.0           ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      ALOR=SQRT((X3-XX1)**2+(Y3-YY1)**2)/2.0         ! LENGTH OF RAY FROM THE STARTING POINT TO THE SQUARE LEAVING POINT.
      ALEN=ALONG+ALOR                                ! THE LENGTH OF THE ABSORBED RAY AT THE SQUARE LEAVING POINT.
      Z2=(-9.8*LOG10(ALEN)+84.6)                     ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE LEAVING THIS SQUARE.
      ALIR=ALEN-ALNG                                 ! LENGTH OF RAY ON ENTERING THIS SQUARE.
      Z1=(-9.8*LOG10(ALIR)+84.6)                     ! TO FIND THE ABSORBED ENERGY OF THE RAY ON ENTERING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100    ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                          ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
10    CONTINUE                                       ! FIND THE ABSORBTION OF THE RAY IN THE NEXT SQUARE THROUGH
                                                     ! WHICH THE RAY PASSES.
      RLOP=RLOP+SQRT((XX1-XX2)**2+(YY1-YY2)**2)/2.0        !UPDATE THE LENGTH OF RAY.
*     TYPE 98,RLOP
      IF (TRAP.EQ.0) TABLE(IXX2,IYY2)=TABLE(IXX2,IYY2)+0.001*Z2     !ABSORBTION DUE TO REFLECTANCE.(10% OF Z2%=0.001*Z2).
      IF (TRAP.EQ.0) RLOP=(10**(0.8633+0.9*LOG10(RLOP)))            !APPARENT LENGTH OF RAY DUE TO REFLECTANCE.
*     TYPE 99,RLOP
      RETURN                                                        ! RETURN TO MAIN PROGRAM TO OBTAIN NEXT RAY.
```

```
C**   **DIRECTION OF RAY IS IN THE FOURTH QUADRANT.**

4     X3=XX1                          ! TO RETAIN THE STARTING COORDINATES OF THIS RAY IE. (XX1,YY1).
      Y3=YY1                          ! AND FOR CONVENIANCE WE SHALL START IN THIS SQUARE.
      DO 1000 NNN=IXX1,IXX2           ! A LOOP. TO ENTER THE RESULTS OF THE ENERGY ABSORBTION OF THE RAY
5000  IX=X3                           ! THE COORDINATES OF THE SQUARE IN WHICH THE RAY STARTS.
      IY=Y3
      IF(Y3.EQ.IY)  IY=IY-1           ! IF THE COORDINATE IS ON THE LINE WE NEED THE SQUARE BELOW.
      X4=IX+1                         ! LAST X COORDINATE IN THIS SQUARE AND FIRST X COORDINATE OF THE NEXT
      IF(X4.LT.XX2)  GO TO  2000      ! TO TEST WETHER THE RAY HAS STOPED SHORT OF THIS COORDINATE OR NOT.
      X4=XX2                          ! TO FIND THE RAY LENGTH IN THIS THE LAST SQUARE USE THE RAYS
      Y4=YY2                          !FINISHING COORDINATES.
      GO TO  3000                     ! TEST TO SEE IF THE RAY PASSES OUT OF THIS SQUARE FROM BELLOW
                                      ! BEFORE IT REACHES THE SIDE OR THE END OF THE RAY.
2000  Y4=RFFM*X4+RFC                  ! TO FIND THE Y COORDINATE ON THE SIDE WALL.
3000  IF(Y4.GE.IY)  GO TO  4000       ! IF TRUE THEN RAY HAS PASSED OUT OF THE SIDE OF THE SQUARE. OR HAS FINISHED.
      Y4=IY                           ! FIND THE COORDINATES WHERE THE RAY LEAVES THE BOTTOM OF THE SQUARE.
      X4=(Y4-RFC)/RFFM
      ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)/2.0             ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      Z1=(-9.8*LOG10(ALONG)+84.6)                      ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE ENTERING THIS SQUARE.
      ALONG=ALONG+ALNG                                 ! LENGTH OF RAY ON LEAVING THIS SQUARE.
      Z2=(-9.8*LOG10(ALONG)+84.6)                      ! TO FIND THE ABSORBED ENERGY OF THE RAY ON LEAVING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100      ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                            ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
      GO TO  5000                                      !FIND THE NEXT SQUARE THROUGH WHICH THE RAY PASSES.
4000  ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)/2.0             ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      Z1=(-9.8*LOG10(ALONG)+84.6)                      ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE ENTERING THIS SQUARE.
      ALONG=ALONG+ALNG                                 ! LENGTH OF RAY ON LEAVING THIS SQUARE.
```

```
      Z2=(-9.8*LOG10(ALONG)+84.6)                          ! TO FIND THE ABSORBED ENERGY OF THE RAY ON LEAVING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100          ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                                ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
1000  CONTINUE                                             ! FIND THE ABSORBTION OF THE RAY IN THE NEXT SQUARE THROUGH
      RLOP=RLOP+SQRT((XX1-XX2)**2+(YY1-YY2)**2)/2.0                    !UPDATE THE LENGTH OF THE RAY .
*     TYPE 98,RLOP
      IF (TRAP.EQ.0) TABLE(IXX2,IYY2)=TABLE(IXX2,IYY2)+0.001*Z2     !ABSORBTION DUE TO REFLECTANCE. (10% OF Z2%=0.001*Z2).
      IF (TRAP.EQ.0) RLOP=(10**(0.8633+0.9*LOG10(RLOP)))             !APPARENT LENGTH OF RAY DUE TO REFLECTANCE.
*     TYPE 99,RLOP
      RETURN                                                          ! RETURN TO MAIN PROGRAM TO OBTAIN NEXT RAY.
```

```
C**     **DIRECTION OF RAY IS IN THE FIRST QUADRANT.**

1       X3=XX1                    ! TO RETAIN THE STARTING COORDINATES OF THIS RAY IE. (XX1,YY1).
        Y3=YY1                    ! AND FOR CONVENIANCE WE SHALL START IN THIS SQUARE.
        DO 100 NN=IXX1,IXX2       ! A LOOP. TO ENTER THE RESULTS OF THE ENERGY ABSORBTION OF THE RAY
                                  ! IN EACH SQUARE INTO THE TABLE OF RESULTS.
500     IX=X3                     ! THE COORDINATES OF THE SQUARE IN WHICH THE RAY IS PASSING.
        IY=Y3
        X4=IX+1                   ! LAST X COORDINATE IN THIS SQUARE AND FIRST X COORDINATE OF THE NEXT
                                  ! SQUARE IF THE RAY PASSES OUT OF THE SIDE OF THE SQUARE.
        IF(X4.LT.XX2)  GO TO  200 ! TO TEST WETHER THE RAY STOPS SHORT OF THIS COORDINATE OR NOT.
        X4=XX2                    ! TO FIND THE RAY LENGTH IN THE LAST SQUARE USE THE RAYS FINISHING
        Y4=YY2                    !COORDINATES.
        GO TO  300                ! TEST TO SEE IF THE RAY PASSES OUT OF THIS SQUARE FROM BELLOW
                                  ! BEFORE IT REACHES THE SIDE OR THE END OF THE RAY.
2       Y4=RFFM*X4+RFC            ! TO FIND THE Y COORDINATE ON THE SIDE WALL.
300     IF(Y4.LT.(IY+1))  GO TO 400 ! IF TRUE RAY PASSES OUT THE SIDE OF THE SQUARE OR STARTED WITHIN IT.
        Y4=IY+1                   ! FIND THE COORDINATES AT WHICH THE RAY LEAVES THE TOP OF THE SQUARE.
        X4=(Y4-RFC)/RFFM
        ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)/2.0            ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
        Z1=(-9.8*LOG10(ALONG)+84.6)                     ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE ENTERING THIS SQUARE.
        ALONG=ALONG+ALNG                                ! LENGTH OF RAY ON LEAVING THIS SQUARE.
*       TYPE 98,Z1
        Z2=(-9.8*LOG10(ALONG)+84.6)                     ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE ENTERING THIS SQUARE.
*       TYPE 99, Z2
              TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100     ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
        X3=X4                                           ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
        Y3=Y4
        GO TO  500                                      !FIND THE NEXT SQUARE THROUGH WHICH THE RAY PASSESS.
400     ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)/2.0            ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
        Z1=(-9.8*LOG10(ALONG)+84.6)                     ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE ENTERING THIS SQUARE.
        ALONG=ALONG+ALNG                                ! LENGTH OF RAY ON LEAVING THIS SQUARE.
        Z2=(-9.8*LOG10(ALONG)+84.6)                     ! TO FIND THE ABSORBED ENERGY OF THE RAY ON LEAVING THIS SQUARE.
              TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100     ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
        X3=X4                                           ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
        Y3=Y4
100     CONTINUE                                        ! FIND THE ABSORBTION OF THE RAY IN THE NEXT SQUARE THROUGH
                                                        ! WHICH THE RAY PASSES.
```

```
      RLOP=RLOP+SQRT((XX1-XX2)**2+(YY1-YY2)**2)/2.0                    !UPDATE THE LENGTH OF THE RAY .
*     TYPE 98,RLOP
      IF (TRAP.EQ.0) TABLE(IXX2,IYY2)=TABLE(IXX2,IYY2)+0.001*Z2   !ABSORBTION DUE TO REFLECTANCE. (10% OF Z2%=0.001*Z2).
      IF (TRAP.EQ.0) RLOP=(10**(0.8633+0.9*LOG10(RLOP)))                !APPARENT LENGTH OF RAY DUE TO REFLECTANCE.
*     TYPE 99,RLOP
      RETURN                                                      ! RETURN TO MAIN PROGRAM TO OBTAIN NEXT RAY.



C**   **DIRECTION OF RAY IS IN THE THIRD QUADRANT.**

3     X3=XX2                       ! TO RETAIN THE FINAL COORDINATES OF THIS RAY IE. (XX2,YY2).
      Y3=YY2                       ! AND FOR CONVENIANCE WE SHALL START IN THIS SQUARE AND WORK BACKWARDS
      DO 10000 NNNN=IXX2,IXX1      ! A LOOP. TO ENTER THE RESULTS OF THE ENERGY ABSORBTION OF THE RAY
                                   ! IN EACH SQUARE INTO THE TABLE OF RESULTS.
50000 IX=X3                        ! THE COORDINATES OF THE SQUARE IN WHICH THE RAY FINISHES.
      IY=Y3
      X4=IX+1                      ! LAST X COORDINATE IN THIS SQUARE AND FIRST X COORDINATE OF THE NEXT
                                   ! SQUARE IF THE RAY PASSES OUT OF THE SIDE OF THE SQUARE.
      IF(X4.LT.XX1)  GO TO  20000  ! TO TEST WETHER THE RAY STOPS SHORT OF THIS COORDINATE OR NOT.
      X4=XX1                       ! TO FIND THE RAY LENGTH IN THIS THE LAST SQUARE USE THE RAYS STARTING
      Y4=YY1                       !COORDINATES.
      GO TO  30000                 ! TEST TO SEE IF THE RAY PASSES INTO THIS SQUARE FROM THE TOP
                                   ! OR STARTS IN THIS SQUARE.
20000 Y4=RFFM*X4+RFC               ! TO FIND THE Y COORDINATE ON THE SIDE WALL.
30000 IF(Y4.LT.(IY+1))  GO TO 40000  ! IF TRUE RAY PASSES OUT THE SIDE OF THE SQUARE OR STARTED WITHIN IT.
      Y4=IY+1                      ! FIND THE COORDINATES WHERE THE RAY ENTERS THE TOP OF THE SQUARE.
      X4=(Y4-RFC)/RFFM
      ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)/2.0           ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      ALOR=SQRT((X3-XX1)**2+(Y3-YY1)**2)/2.0         ! LENGTH OF RAY FROM THE STARTING POINT TO THE SQUARE LEAVING POINT.
      ALEN=ALONG+ALOR                                ! THE LENGTH OF THE ABSORBED RAY AT THE SQUARE LEAVING POINT.
      Z2=(-9.8*LOG10(ALEN)+84.6)                     ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE LEAVING THIS SQUARE.
      ALIR=ALEN-ALNG                                 ! LENGTH OF RAY ON ENTERING THIS SQUARE.
      Z1=(-9.8*LOG10(ALIR)+84.6)                     ! TO FIND THE ABSORBED ENERGY OF THE RAY ON ENTERING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100    ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                          ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4
      GO TO  50000                                   !FIND THE NEXT SQUARE THROUGH WHICH THE RAY PASSES.
40000 ALNG=SQRT((X4-X3)**2+(Y4-Y3)**2)/2.0           ! TO FIND THE LENGTH OF THE RAY THROUGH THIS SQUARE.
      ALOR=SQRT((X3-XX1)**2+(Y3-YY1)**2)/2.0         ! LENGTH OF RAY FROM THE STARTING POINT TO THE SQUARE LEAVING POINT.
      ALEN=ALONG+ALOR                                ! THE LENGTH OF THE ABSORBED RAY AT THE SQUARE LEAVING POINT.
      Z2=(-9.8*LOG10(ALEN)+84.6)                     ! TO FIND THE ABSORBED ENERGY OF THE RAY BEFORE LEAVING THIS SQUARE.
      ALIR=ALEN-ALNG                                 ! LENGTH OF RAY ON ENTERING THIS SQUARE.
      Z1=(-9.8*LOG10(ALIR)+84.6)                     ! TO FIND THE ABSORBED ENERGY OF THE RAY ON ENTERING THIS SQUARE.
            TABLE(IX,IY)=TABLE(IX,IY)+(Z1-Z2)/100    ! AMOUNT OF ENERGY ABSORBED IN THIS SQUARE COMPARED TO THAT OF ONE RAY
      X3=X4                                          ! THE COORDINATES OF THE RAY ENTERING THE NEXT SQUARE.
      Y3=Y4                                          ! FIND THE ABSORBTION OF THE RAY IN THE NEXT SQUARE THROUGH
10000 CONTINUE                                       ! WHICH THE RAY PASSES.
                                                                !UPDATE THE LENGTH OF THE RAY .
      RLOP=RLOP+SQRT((XX1-XX2)**2+(YY1-YY2)**2)/2.0
*     TYPE 98,RLOP
```

```
      IF (TRAP.EQ.0) TABLE(IXX2,IYY2)=TABLE(IXX2,IYY2)+0.001*Z2        !ABSORBTION DUE TO REFLECTANCE. (10% OF Z2%=0.001*Z2).
      IF (TRAP.EQ.0) RLOP=(10**(0.8633+0.9*LOG10(RLOP)))                 !APPARENT LENGTH OF RAY DUE TO REFLECTANCE.
*     TYPE 99,RLOP
      RETURN                                                           ! RETURN TO MAIN PROGRAM TO OBTAIN NEXT RAY.


98    FORMAT('BEFORE=',F8.4)
99    FORMAT('AFTER=',F8.4)
      END
```

```
*
*PROGRAM:      TABCNIT.FOR
*WRITTEN BY:   R.W.ELLIOTT.

      SUBROUTINE TABCNIT   (TABTOT,TABLE,TOTENY,TENEGY,ANSWER,L)
      DIMENSION TABLE(20,30),TABTOT(20,30),ANSWER(13,8)
      DO 10 N=1,30
      DO 20 M=1,18
      TABLE(M,N)=TABLE(M,N)/ANSWER(L,2)*100
      TABTOT(M,N)=TABTOT(M,N)+TABLE(M,N)
      TABLE(20,N)=TABLE(20,N)+TABLE(M,N)
      TOTENY=TOTENY+TABLE(M,N)
 20   CONTINUE
      TABTOT(20,N)=TABTOT(20,N)+TABLE(20,N)
 10   CONTINUE
      TENEGY=TENEGY+TOTENY
      RETURN
      END
```

```
*
*PROGRAM:      TRAP2T.FOR
*WRITTEN BY:   R..W.ELLIOTT.

      SUBROUTINE    TRAP2T(X2,Y2,RLOP,COL)              !COORDINATES AND LENGTH OF RAY ON ENTERING THE COLLECTOR.
      DIMENSION     COL(20),COLP(20)                            !CREATE TWO ONE  DIMENSIONAL ARRAYS.
      INTEGER*4     IX
      IX=2*X2+10                                        !RIGHT SHIFT FOR USE WITH ARRAYS.
      COL(IX)=COL(IX)+((84.6-9.8*LOG10(RLOP))/100)      !ENERGY REACHING THE COLLECTOR.
      RETURN                                            !RETURN TO MAIN PROGRAM.
      END
```

```
*
*PROGRAM:      ENGEN.FOR
*WRITTEN BY:   R..W.ELLIOTT.

************************************************
*             program: ENGEN.FOR               *
************************************************

*      This program converts the energy generation percentages as compiled by RWE11.FOR and RWE11T.FOR
*      into energy gereration per unit volumes.

*      Input file:-    ENERGY_TEMP.DAT
*      Output file:-   ENGEN.DAT

*      To change the elemental size the value of L must be changed.

*      DIMENSION      E(20,31)

       INTEGER*4      I,J,IT,JT,LQ,PHLOSS
       REAL*4         E(20,31),COLP(20),L,Q,S,PI,MEW


                                                 !LQ is the solar incidence angle.
       L=0.5                                     !Elemental size in cm.

       IF (L.EQ.0.5) THEN
              JT=31                                      !Vertical dimension of input file.
              IT=16                                      !Horizontal dimension of input file.
              OPEN(UNIT=30,NAME='ENERGY_TEMPT.DAT',TYPE='UNKNOWN')
       ELSE
              JT=16                                      !Vertical dimension of input file.
              IT=8                                       !Horizontal dimension of input file.
              OPEN(UNIT=30,NAME='ENERGY_TEMP.DAT',TYPE='UNKNOWN')
       ENDIF

       OPEN(UNIT=40,NAME='ENGEN.DAT',TYPE='UNKNOWN')

       S=2.97
       PI=3.141592653589793238

********************************
*      Read input file         *
********************************

       DO 80 P=1,7                           !Repeat for all angles of incidence.
       IF (L.EQ.0.5) THEN
              DO 10 J=1,JT
              READ(30,1000) (E(I,J),I=1,IT)
10            CONTINUE
       ELSE
              DO 15 J=1,JT
              READ(30,2000) (E(I,J),I=1,IT)
15            CONTINUE
       ENDIF
       READ(30,3000) LQ,COLP(20)
       Q=(LQ-270)*PI/180

********************************
*      Process Data            *
********************************


       DO 20 I=1,IT
       DO 30 J=1,JT-1
*      E(I,J)=(E(I,J)*S*COS(Q))/(L**2)           !Energy generation per unit volume.
       E(I,J)=(E(I,J)*S)/(L**2)                  !Energy generation per unit volume.
```

```
30      CONTINUE
20      CONTINUE

*********************************
*       Write to data file      *
*********************************

        IF (L.EQ.0.5) THEN
                DO 40 J=1,JT-1
                WRITE(40,1000) (E(I,J),I=1,IT)
40              CONTINUE
        ELSE
                DO 50 J=1,JT-1
                WRITE(40,2000) (E(I,J),I=1,IT)
50              CONTINUE
        ENDIF

*********************************
*       HEAT LOSS FROM RECEIVER *
*********************************

        DO 90 I=1,IT
        COLP(I)=E(I,JT)
90      CONTINUE

        DO 70 PHLOSS=0,100,25                   !Repeat for different percentage heat loss.
        MEW=COLP(20)*(100-PHLOSS)/100.0

        DO 60 I=1,IT
        E(I,JT)=COLP(I)*PHLOSS/100.0
*       E(I,JT)=(E(I,JT)*S*COS(Q))/(L**2)                !Energy generation per unit volume.
        E(I,JT)=(E(I,JT)*S)/(L**2)                  !Energy generation per unit volume.

60      CONTINUE

*********************************
*       Write to data file      *
*********************************
        IF (L.EQ.0.5) THEN
                WRITE(40,1000) (E(I,JT),I=1,IT)
        ELSE
                WRITE(40,2000) (E(I,J),I=1,IT)
        ENDIF
        WRITE(40,3000) LQ,COLP(20),MEW
70      CONTINUE

80      CONTINUE

1000    FORMAT(2X,16F8.4)
2000    FORMAT(5X,8F14.10)
3000    FORMAT(5X,I3,5X,F5.2,5X,F5.2)
        END
```

```
*
*PROGRAM:       THMRES.FOR
*WRITTEN BY:    R.W.ELLIOTT.

****************************************
*       program: THMRES.FOR            *
*       CREATED: 21:1:87               *
****************************************

*       This program calculates the thermal resistances within a grid of temperature nodes
*       for the boundary conditions defined by the solar collector shape.
*

*       To change the element size just alter the value of L.
*       Note check the dimension statement is large enough.

*       DIMENSION       R(100,100,2)

        INTEGER*4       I,J,T,IT,JT
        REAL*4          R(100,100,2),S,H,KG,KH,KI,L,XD,X

        OPEN(UNIT=31,NAME='THERMRES.DAT',TYPE='UNKNOWN')

        S=4.0                                                   !X coordinate of a vertical line of symmetry.
        H=15.5                                                  !Height of collector plus glass top.
        T=50                                                    !offset parameter for arraysubscipts.
        L=0.5                                                   !L is the elemental width.
        KG=1.2                                                  !Thermal conductivity of glass.
        KH=0.15                                                 !Thermal conductivity of hyvis.
        KI=0.02                                                 !Thermal conductivity of insulation foam.
        KR=400

****************************************
*       Set rows and columns of grid   *
****************************************

        IT=INT((S-L)/L+0.1)                                     !IT=  The number of +ve horizontal elements.
        JT=INT((H-L)/L+0.1)                                     !JT=  The number of +ve vertical elements.

        DO 100 I=-1,IT                                          !Process each column.
        DO 200 J=0,JT                                           !Process each row.

        XD=59-SQRT(3364-(J*L+L/2)**2)                           !The horizontal distance from the y axis to the side reflecting surface.
        X=XD-(I*L)                                              !The horizontal distance from the gride side to the side reflecting surface.

*   *************************************
*       Vertical Resistances           *
****************************************

********        Cases to consider 1h,1i,2g,3,4g,4h,4i,5  ********

        IF ((J*L+L/2).LT.15) THEN                               !Cases 1h,1i,3,4h,4i,5
            IF (((J+1)*L+L/2).GT.15) THEN                       !Case 1i
                IF (X.LE.0) THEN                                !Case 1i insulation to glass
                    R(T+I,T+J,2)=(KI+KG)/(2.0*KI*KG)            !Case 1i
                ELSE                                            !Cases 1h,3
                    IF (X.LT.L) THEN                            !Case 3
                        R(T+I,T+J,2)=1.0/(2*KG)+L/(2*(X*KH+(L-X)*KI))   !Case 3
                    ELSE                                        !Case 1h Hyvis to glass.
                        R(T+I,T+J,2)=(KH+KG)/(2.0*KH*KG)        !Case 1h
                    ENDIF
                ENDIF
            ELSE                                                !Cases 4h,4i,5
                IF (X.LE.0) THEN                                !Case 4i
                    R(T+I,T+J,2)=1.0/KI                         !Case 4i insulation.
                ELSE                                            !Cases 4h,5
                    IF (X.LT.L) THEN                            !Case 5
                        R(T+I,T+J,2)=L/(X*KH+(L-X)*KI)          !Case 5
                    ELSE                                        !Case 4h
                        R(T+I,T+J,2)=1.0/KH                     !Case 4h hyvis.
```

```
                        ENDIF
                ENDIF
        ENDIF
ELSE
        IF (((J+1)*L+L/2).GT.H) THEN                              !Cases 2g,4g
                R(T+I,T+J,2)=1.0/(2.0*KG)                         !Case 2g
        ELSE                                                      !Case 2g
                R(T+I,T+J,2)=1.0/KG                               !Case 4g
        ENDIF                                                     !Case 4g
ENDIF

****************************************
*       Horizontal Resistances         *
****************************************

      X=XO-(I*L+L/2.0)                          !X= distance from temperature node to boundary.

********        Cases to consider 6,7h,7i,7g      ********
      IF ((J*L+L/2).GT.15) THEN                          !Case 7g
              R(T+I,T+J,1)=1.0/KG                        !Case 7g Just glass.
      ELSE                                               !Cases 6,7h,7i
              IF (X.LE.0) THEN                           !Case 7i
                      R(T+I,T+J,1)=1.0/KI                !Case 7i Just insulation.
              ELSE                                       !Cases6,7h
                      IF (X.LT.L) THEN                   !Case 6
                              R(T+I,T+J,1)=(X*KI+(L-X)*KH)/(L*KH*KI)  !Case 6
                      ELSE                               !Case 7h
                              R(T+I,T+J,1)=1.0/KH        !Case 7h Just hyvis.
                      ENDIF
              ENDIF
      ENDIF

****************************************
*       Symmetrical mapping            *
****************************************

      R(T-(I+1),T+J,2)=R(T+I,T+J,2)
      R(T-(I+2),T+J,1)=R(T+I,T+J,1)
200   CONTINUE
100   CONTINUE


****************************************
*       Below receiver insulation      *
****************************************

********        Cases to consider 2i,4i          ********
      DO 300 I=(-(IT+1)),IT
      DO 400 J=(-INT(15/L+0.1)-1),(-1)

      IF ((J*L).LT.-15) THEN                        !Case 2i
              R(T+I,T+J,2)=1.0/(2.0*KI)                   !Case 2i insulation to air.
      ELSE                                          !Case 4i
              R(T+I,T+J,1)=1.0/KI                   !Case 4i
              R(T+I,T+J,2)=1.0/KI                   !Case 4i
      ENDIF

400   CONTINUE
300   CONTINUE


      ITR=INT(1.0/L+0.1)                            !IT=  The number of +ve elements used for the receiver.

      DO 460 I=-1,ITR-1
      DO 470 J=(-ITR-1),ITR-1

**********************************************
*       Vertical receiver resistances        *
**********************************************
```

```
********        Cases to consider 1ri,1rh,4r    ********

      IF ((J*L).LT.-1) THEN                             !Case 1ri
            R(T+I,T+J,2)=(KR+KI)/(2.0*KR*KI)            !Case 1ri insulation to receiverplate.
      ELSE                                              !Cases 1rh,4r
            IF ((J*L+L).LT.1) THEN                      !Case 4r
                  R(T+I,T+J,2)=1.0/KR                   !Case 4r Using thermal conductivity of 400 w/(mk) for the receiver.
            ELSE                                        !Case 1rh
                  R(T+I,T+J,2)=(KR+KH)/(2.0*KR*KH)      !Case 1rh receiver to hyvis.
            ENDIF
      ENDIF

*************************************************
*     Horizontal receiver resistances           *
*************************************************

********        Cases to consider 1ri,4r                ********

      IF (J.GT.(-ITR-1)) THEN                                   !This value only has vertical restances.
            IF (((I+1)*L+L/2).GT.1) THEN                        !Case 1ri
                  R(T+I,T+J,1)=(KR+KI)/(2.0*KR*KI)              !Case 1ri insulation to receiverplate.
            ELSE                                                !Case 4r
                  R(T+I,T+J,1)=1.0/KR                           !Case 4r Using thermal conductivity of 400 w/(mk) for the rec
eiver.
            ENDIF
      ENDIF

****************************************
*     Symmetrical mapping              *
****************************************

      R(T-(I+1),T+J,2)=R(T+I,T+J,2)
      R(T-(I+2),T+J,1)=R(T+I,T+J,1)

470   CONTINUE
460   CONTINUE


*************************************************
*     CREATE FILE=THERMRES.DAT                  *
*************************************************

      DO 500 Z=1,2

      IF (Z.EQ.1) THEN
            WRITE(31,3000)
      ELSE
            WRITE(31,2000)
      ENDIF

      DO 700 J=JT,(-INT(15/L+0.1)-1),-1

      IF (L.EQ.0.5) THEN
            WRITE(31,1000) (R(T+I,T+J,Z),I=(-(IT+1)),IT)
      ELSE
            WRITE(31,4000) (R(T+I,T+J,Z),I=(-(IT+1)),IT)
      ENDIF
700   CONTINUE
500   CONTINUE

1000  FORMAT(2X,17F8.4)
2000  FORMAT(5X' **********VERTICAL THERMAL RESISTANCES******** ')
3000  FORMAT(5X' **********HORIZONTAL THERMAL RESISTANCES******** ')
4000  FORMAT(5X,8F14.10)
      END
```

F04ATF – NAG FORTRAN Library Routine Document

NOTE: before using this routine, please read the appropriate implementation document to check the interpretation of ***bold italicised*** terms and other implementation-dependent details. The routine name may be precision-dependent.

1. Purpose

F04ATF calculates the accurate solution of a set of real linear equations with a single right hand side, Ax=b, by Crout's factorisation method.

2. Specification

```
      SUBROUTINE F04ATF (A, IA, B, N, C, AA, IAA, WKS1, WKS2,
     1   IFAIL)
C     INTEGER IA, N, IAA IFAIL
C     real A(IA,N), B(N), C(N), AA(IAA,N), WKS1(N), WKS2(N)
```

3. Description

Given a set of linear equations, Ax = b, the routine first decomposes A using Crout's factorisation with partial pivoting PA = LU, where P is a permutation matrix, L is lower triangular and U is unit upper triangular. An approximation to x is found by forward and backward substitution in Ly = Pb and Ux = y. The residual vector r = b – Ax is then calculated and a correction, d, to x is found by the solution of LUd = r. x is replaced by (x+d) and the process repeated until full machine accuracy is obtained. ***Additional precision*** accumulation of innerproducts is used throughout the calculation.

4. References

[1] WILKINSON, J.H. and REINSCH, C.
Handbook for Automatic Computation.
Volume II, Linear Algebra.
Springer-Verlag, 1971, pp. 93–110.

5. Parameters

A – ***real*** array of DIMENSION (IA,p) where $p \geq N$.

Before entry, A must contain the elements of the real matrix.

Unchanged on exit.

IA – INTEGER.

On entry, IA must specify the first dimension of array A as declared in the calling (sub)program.
$IA \geq N$.

Unchanged on exit.

B – ***real*** array of DIMENSION at least (N).

Before entry, B must contain the elements of the right hand side. (See Section 11).

Unchanged on exit.

N – INTEGER.

On entry, N must specify the order of matrix A.

Unchanged on exit.

C – ***real*** array of DIMENSION at least (N).

On successful exit, C will contain the solution vector.

AA – ***real*** array of DIMENSION (IAA,q) where $q \geq N$.

Used as working space.

On successful exit, AA will contain the LU decomposition.

IAA – INTEGER.

On entry, IAA must specify the first dimension of array AA as declared in the calling (sub)program.
$IAA \geq N$.

Unchanged on exit.

WKS1 – ***real*** array of DIMENSION at least (N).

WKS2 – ***real*** array of DIMENSION at least (N).

Used as working space.

IFAIL – INTEGER.

On entry, IFAIL must be set to 0 or 1. For users not familiar with this parameter (described in Chapter P01) the recommended value is 0.

Unless the routine detects an error (see next section), IFAIL contains 0 on exit.

6. Error Indicators and Warnings

Errors detected by the routine:–

IFAIL = 1

The matrix A is singular, possibly due to rounding errors.

IFAIL = 2

The matrix A is too ill-conditioned to produce a correctly rounded solution.

7. Auxiliary Routines

Details are distributed to sites in machine-readable form.

8. Timing

The time taken is approximately proportional to N^3.

9. Storage

There are no internally declared arrays.

10. Accuracy

The computed solutions should be correct to full machine accuracy. For a detailed error analysis see [1], page 107.

11. Further Comments

The routine **must not** be called with the same name for parameters B and C.

12. Keywords

Accurate Solution of Linear Equations,
Crout Factorisation,
Real Matrix,
Single Right Hand Side.

13. Example

To solve the set of linear equations $Ax = b$ where

$$A = \begin{pmatrix} 33 & 16 & 72 \\ -24 & -10 & -57 \\ -8 & -4 & -17 \end{pmatrix} \text{ and } b = \begin{pmatrix} -359 \\ 281 \\ 85 \end{pmatrix}$$

13.1. Program Text

WARNING: This **single precision** example program may require amendment for certain implementations. The results produced may not be the same. If in doubt, please seek further advice (see **Essential Introduction** to the Library Manual).

```
C     F04ATF EXAMPLE PROGRAM TEXT
C     NAG COPYRIGHT 1975
C     MARK 4.5 REVISED
C
      REAL A(5,5), B(5), C(5), AA(5,5), WKS1(18), WKS2(3)
      INTEGER NIN, NOUT, I, N, J, IA, IAA, IFAIL
      DATA NIN /5/, NOUT /6/
      READ (NIN,99999) (WKS1(I),I=1,7)
      WRITE (NOUT,99997) (WKS1(I),I=1,6)
      N = 3
      READ (NIN,99998) ((A(I,J),J=1,N),I=1,N), (B(I),I=1,N)
      IA = 5
      IAA = 5
      IFAIL = 1
      CALL F04ATF(A, IA, B, N, C, AA, IAA, WKS1, WKS2, IFAIL)
      IF (IFAIL.EQ.0) GO TO 20
      WRITE (NOUT,99996) IFAIL
      STOP
   20 WRITE (NOUT,99995) (C(I),I=1,N)
      STOP
99999 FORMAT (6A4, 1A3)
```

```
99998 FORMAT (3F5.0)
99997 FORMAT (4(1X/), 1H , 5A4, 1A3, 7HRESULTS/1X)
99996 FORMAT (25HOERROR IN F04ATF IFAIL = , I2)
99995 FORMAT (10HOSOLUTIONS/(1H , F4.1))
      END
```

13.2. Program Data

```
F04ATF EXAMPLE PROGRAM DATA
   33   16   72
  -24  -10  -57
   -8   -4  -17
 -359  281   85
```

13.3. Program Results

```
 F04ATF EXAMPLE PROGRAM RESULTS

 SOLUTIONS
  1.0
 -2.0
 -5.0
```

```
**************************************************
*       program          :FINDIF.FOR             *
*       written by       :R.W.ELLIOTT.           *
**************************************************

*       This program creates the matrix of the finite difference equations for the temperature nodes
*       at the centre of each element.

*       Input file:-    ENGEN.DAT
*                       THERMRES.DAT

*       Output file:-   MATA.DAT
*                       MATB.DAT
*                       MATTEMP.DAT

*       To change the elemental size the value of L must be altered.
*       The start and stop dimensions must also be correct.


        INTEGER*4       LO,I,J,K,N,M,NI,NF,MI,MF,E
        REAL*4          R(16,62,2),G(16,62),A(976,976),B(976),L,COLP,MEW,TAM
        CHARACTER       DUMMY*48


        OPEN(UNIT=30,NAME='[SC.RWELLIOTT.SESS86] THERMRES.DAT',TYPE='OLD')
        OPEN(UNIT=31,NAME='[SC.RWELLIOTT.SESS86] ENGEN.DAT',TYPE='OLD')
        OPEN(UNIT=32,NAME='[SC.RWELLIOTT.SESS86] MATA.DAT',TYPE='NEW')
        OPEN(UNIT=33,NAME='[SC.RWELLIOTT.SESS86] MATB.DAT',TYPE='NEW')
        OPEN(UNIT=34,NAME='[SC.RWELLIOTT.SESS86] MATTEMP.DAT',TYPE='NEW')

        L=0.005                                 !Elemental size in metres.
        TAM=20.0                                !Temperature ambient.

        IF(L.EQ.0.005) THEN
                MI=1                                    !Initial value of M (horizontal)
                NI=2                                    !Initial value of N (vertical)
                MF=16                                   !Final   value of M (horizontal)
                NF=62                                   !Final   value of N (vertical)
        ELSE
                MI=1                                    !Initial value of M (horizontal)
                NI=2                                    !Initial value of N (vertical)
                MF=8                                    !Final   value of M (horizontal)
                NF=32                                   !Final   value of N (vertical)
        ENDIF

*********************************
*       read input files        *
*********************************


*****************************************
*       read thermal resistances file   *
*****************************************


        DO 10 K=1,2
        READ(30,1000) DUMMY
        DO 20 J=NF,1,-1
        IF(L.EQ.0.005) THEN
                READ(30,2001) (R(I,J,K),I=1,MF)         !Thermal resistances.

        ELSE
                READ(30,2000) (R(I,J,K),I=1,MF)         !Thermal resistances.
        ENDIF
```

```
20      CONTINUE
10      CONTINUE

*************************************************************************
*       EVALUATE THE TEMPERATURES FOR VARIOUS INSOLATION INTENSITIES    *
*************************************************************************

        DO 700 E=900,100,-400
        REWIND (UNIT=31)


*********************************************************
*       LOOP FOR DIFFERENT ANGLES OF INCIDENCE          *
*********************************************************

        DO 300 P=1,7

*****************************************
*       READ ENERGY GENERATION FILE     *
*****************************************

        DO 40 J=NF,NI,-1
        IF(L.EQ.0.005) THEN
                IF (J.GE.(INT((NF+4.1)/2))) THEN
                        READ(31,2001) (G(I,J),I=MI,MF)          !Energy generation.
*       type*,j,g(8,j)
                ELSE
                        DO 46 I=MI,MF
                        G(I,J)=0
46                      CONTINUE
                ENDIF
        ELSE
                IF (J.GE.(INT((NF+4.1)/2))) THEN
                        READ(31,2000) (G(I,J),I=MI,MF)
                ELSE
                        DO 45 I=MI,MF
                        G(I,J)=0
45                      CONTINUE
                ENDIF
        ENDIF

40      CONTINUE


************************************************
*       LOOP FOR DIFFERENT HEAT LOSSES         *
************************************************

        DO 400 H=0,100,25

        J=INT((NF+2.1)/2)
        IF(L.EQ.0.005) THEN
                READ(31,2001) (G(I,J),I=MI,MF)
*               type*,(G(I,J),I=MI,MF)
        ELSE
                READ(31,2000) (G(I,J),I=MI,MF)
        ENDIF
        READ(31,1) LQ,COLP,MEW
*       TYPE*,LQ,COLP,MEW

*       WRITE(34,2010)
*       DO 60 J=NF,NI,-1
*       WRITE(34,2001) (G(I,J),I=MI,MF)
*60     CONTINUE

********************************
```

```
*       INITIALIZE ARRAYS       *
*********************************

        DO 11 M=1,976
        DO 22 N=1,976
        A(M,N)=0
22      CONTINUE
        B(M)=0
11      CONTINUE

*************************************************
*       Create finite difference equations      *
*************************************************

        DO 100 M=MI,MF                          !Horizontal
        DO 200 N=NI,NF                          !Vertical

        T=(N-NI)*MF+M                           !The position in each array associated with the temperature node (n,m).
        IF((M-1).GE.MI) THEN                            !Symmetrical dQ/dx=0
                A(T-1,T)=A(T-1,T)+ 1.0/R(M-1,N,1)
                A(T,T)=A(T,T)-1.0/R(M-1,N,1)
        ENDIF

        IF ((M+1).LE.MF) THEN                           !Symmetrical dQ/dx=0
                A(T+1,T)=A(T+1,T)+ 1.0/R(M,N,1)
                A(T,T)=A(T,T)-1.0/R(M,N,1)
        ENDIF

        IF ((N-1).GE.NI) THEN                           !Insulation with ambient.
                A(T-MF,T)=A(T-MF,T)+ 1.0/R(M,N-1,2)
        ELSE
                B(T)=B(T)-TAM/R(M,N-1,2)
        ENDIF
                A(T,T)=A(T,T)-1.0/R(M,N-1,2)

        IF ((N+1).LE.NF) THEN                           !Glass top with ambient.
                A(T+MF,T)=A(T+MF,T)+ 1.0/R(M,N,2)
        ELSE
                B(T)=B(T)-TAM/R(M,N,2)
        ENDIF
                A(T,T)=A(T,T)-1.0/R(M,N,2)
                B(T)=B(T)-L**2*G(M,N)*E
200     CONTINUE
100     CONTINUE

*****************************************
*       File the matrices [A] and [B]   *
*****************************************

        REWIND (UNIT=32)
        REWIND (UNIT=33)

        DO 500 J=1,T
        DO 600 I=1,T
        WRITE(32,4000) A(I,J)
600     CONTINUE
        WRITE(33,4000) B(J)
500     CONTINUE

        TYPE*,LQ,E,COLP,MEW

*****************************************
*       Solve the matrix equation       *
*****************************************

        CALL SOLMAT(LQ,COLP,TAM,E,MEW,MF)
```

```
400     CONTINUE
300     CONTINUE
700     CONTINUE

1       FORMAT(5X,I3,5X,F5.2,5X,F5.2)
1000    FORMAT(5X,A48)
2000    FORMAT(5X,8F14.10)
2001    FORMAT(2X,17F8.4)
4000    FORMAT(F12.5)
5000    FORMAT(F5.2)
2010    FORMAT(5X,'ENERGY GENERATION FILE')

        END
```

```
*
*PROGRAM:      SOLMAT.FOR
*WRITTEN BY:   R.W.ELLIOTT.


********************************
*     SOLMAT.FOR              *
********************************

*     This program solves the matrix equation [A][x]=[B]
*     The solution to the temperature nodes will be found in file MATTEMP.DAT

      SUBROUTINE SOLMAT(LQ,COLP,TAM,E,MEW,MF)

      INTEGER*4     LQ,E
      INTEGER*4     I,J,TJ,N,MF,IFAIL
      REAL*4        COLP,TAM,MEW,X,A(976,976),B(976)
      REAL*4        AA(976,976),C(976),WKS1(976),WKS2(976)


      N=976
      IFAIL=1
****************************************
*     INITIALIZE VARIABLES            *
****************************************

      DO 40 I=1,N
      WKS1(I)=0
      WKS2(I)=0
      C(I)=0
      DO 50 J=1,N
      AA(I,J)=0
50    CONTINUE
40    CONTINUE


****************************************
*     Input matrix [A] and [B]        *
****************************************

      REWIND (UNIT=32)
      REWIND (UNIT=33)
      DO 10 I=1,N
      DO 20 J=1,N
      READ(32,400) A(I,J)
20    CONTINUE
      READ(33,400) B(I)
10    CONTINUE

************************
*     Solve matrix    *
************************

      CALL F04ATE(A,N,B,N,C,AA,N,WKS1,WKS2,IFAIL)

      IF (IFAIL.EQ.0) THEN

********************************
*     OUTPUT SOLUTION         *
********************************

      L=LQ-270
      WRITE(34,1000) L
      WRITE(34,2000) E
      WRITE(34,3000) MEW
      WRITE(34,3500) TAM
      X=(C(N/2)-TAM)/E
      WRITE(34,4000) X

      DO 30 J=(N-MF+1),1,(-MF)
```

```
      TJ=J
      WRITE(34,5000) (C(TJ),TJ=TJ,(TJ+MF-1))
30    CONTINUE

      ELSE
      WRITE(34,1) IFAIL
      ENDIF
1     FORMAT(5X,'ERROR IN F04ATE  IFAIL=',I2)
400   FORMAT(F12.5)
1000  FORMAT(5X,'The angle of the incident radiation is ',I3,' degrees.')
2000  FORMAT(5X,'With insolation of ',I4,'  Watts per metre squared.')
3000  FORMAT(5X,'The efficiency of the collector is ',F5.2,'%')
3500  FORMAT(5X,'The ambient temperature is ',F5.2,'degrees centigrade.')
4000  FORMAT(15X,'DT/E = ',F6.3)
5000  FORMAT(2X,16F8.2)
      END
```

```
*
*PROGRAM:       INSPEC-MAT.FOR
*WRITTEN BY:    R.W.ELLIOTT.

********************************
*      INSPEC-MAT.FOR          *
********************************

      INTEGER*4        I,J
      REAL*4           A(240,240),B(240)

      OPEN(UNIT=32,NAME='MATA.DAT',TYPE='UNKNOWN')
      OPEN(UNIT=33,NAME='MATB.DAT',TYPE='UNKNOWN')
      OPEN(UNIT=34,NAME='TEMP.DAT',TYPE='UNKNOWN')

      DO 10 I=1,240
      DO 20 J=1,240
      READ(32,4000) A(I,J)
20    CONTINUE
      READ(33,4000) B(I)
10    CONTINUE

4000  FORMAT(F16.10)

      TYPE6000
      ACCEPT*,I
      WRITE(34,7000) I

      DO 30 J=233,1,-8
      NU=J
      WRITE(34,5000) (A(I,NU),NU=NU,NU+7)
30    CONTINUE
      WRITE(34,5000) B(I)

5000  FORMAT(2X,8F16.10)
6000  FORMAT(5X,'ENTER VALUE OF TEMPERATURE NODE  ')
7000  FORMAT('+',I4)
      END
```

```
*
*************************************************
*       program:        MASCAP.FOR                *
*       Written by:     R..W.ELLIOTT.             *
*       CREATED:        11:3:87                   *
*************************************************

*       This program calculates the energy required to raise the elemental volume
*       between two temperature nodes through 1C.(J/C).
*       for the boundary conditions defined by the solar collector shape.
*

*       To change the element size just alter the value of L.
*       Note check the dimension statement is large enough.


        INTEGER*4       I,J,T,IT,JT
        REAL*4          MC(100,100),S,H,CG,CH,CI,pG,pH,pI,L,LM,XD,X,MCR,MCRE

        OPEN(UNIT=31,NAME='EJPDC.DAT',TYPE='UNKNOWN')

        S=4.0                                                   !X coordinate of a vertical line of symmetry.
        H=15.5                                                  !Height of collector plus glass top.
        T=50                                                    !offset parameter for array subscipts.
        L=0.5                                                   !L is the elemental width in cm.
        LM=0.005
        CG=837                                                  !Thermal capacity of glass.
        CH=2000                                                 !Thermal capacity of hyvis.
        CI=1045                                                 !Thermal capacity of insulation foam.
        pG=2500                                                 !Density of glass.
        pH=921                                                  !Density of hyvis.
        pI=70                                                   !Density of insulation.
        MCR=487.51823                                                   !The energy per degree for the whole receiver.

****************************************
*       Set rows and colums of grid    *
****************************************

        IT=INT((S-L)/L+0.1)                             !IT=  subscript for the most +ve horizontal element.
        JT=INT((H-L)/L+0.1)                             !JT=  subscript for the most +ve vertical element.

        DO 100 I=0,IT                                   !Process each colum.
        DO 200 J=0,JT                                   !Process each row.

        XD=59-SQRT(3364-(J*L+L/2)**2)                   !The horizontal distance from the y axis to the side reflecting surface.
        X=XD-(I*L)                                      !The horizontal distance from the gride side to the side reflecting surface.

****************************************
*       Mass Capasitances              *
****************************************

********        Cases to consider 1g,1h,1i,2,3   ********

                                                                        !Cases 1h,1i,3
        IF ((J*L+L/2).LT.15) THEN                                       !Case 1i
                IF (X.LE.0) THEN                                        !Case 1i
                        MC(T+I,T+J)=LM**2*(pI*CI)                       !Case 1h,3
                ELSE                                                    !Case 3
                        IF (X.LT.L) THEN                                !Case 3
                                MC(T+I,T+J)=LM*(X/100*pH*CH+(LM-X/100)*pI*CI)   !Case 1h
                        ELSE                                            !Case 1h
                                MC(T+I,T+J)=LM**2*(pH*CH)
                        ENDIF
                ENDIF                                                   !Cases 1g,2
        ELSE                                                            !Case 2
                IF (((J+1)*L+L/2).GT.H) THEN                            !Case 2
                        MC(T+I,T+J)=LM**2*(pG*CG)/2.0
```

```
          ELSE                                              !Case 1g
                MC(T+I,T+J)=LM**2*(pG*CG)                   !Case 1g
          ENDIF
      ENDIF

***************************************
*     Symmetrical mapping           *
***************************************

      MC((T-I-1),T+J)=MC(T+I,T+J)
200   CONTINUE
100   CONTINUE


***************************************
*     Below receiver insulation     *
***************************************

********        Cases to consider 1i          ********
      DO 300 I=(-IT-1),IT
      DO 400 J=(-INT(15/L+0.1)-1),(-1)

      MC(T+I,T+J)=LM**2*(pI*CI)                             !Case 1i

4ω    CONTINUE
300   CONTINUE

************************
*     The Receiver    *
************************

      ITR=INT(1.0/L-1)                                      !ITR=  subscipt for the most +ve element used for the
 receiver.
      MCRE=MCR/(2*(ITR+1))**2

      DO 460 I=(-ITR-1),ITR
      DO 470 J=(-ITR-1),ITR

***********************************************
*     receiver mass capasitances              *
***********************************************

********        Cases to consider 1r    *********

      MC(T+I,T+J)=MCRE                  !Case 1r Using mass capacitance value of MCR from notes.

470   CONTINUE
460   CONTINUE


*******************************
*     CREATE FILE=EJPDC.DAT  *
*******************************


      DO 700 J=JT,(-INT(15/L+0.1)),-1

      IF (L.EQ.0.5) THEN
            WRITE(31,1000) (MC(T+I,T+J),I=(-IT-1),IT)
      ELSE
            WRITE(31,4000) (MC(T+I,T+J),I=(-IT-1),IT)
      ENDIF
700   CONTINUE

1000  FORMAT(2X,17F8.4)
4000  FORMAT(5X,8F14.10)
```

```
*
*PROGRAM:       HEICAP.FOR
*WRITTEN BY:    R.W.ELLIOTT.

************************************************
*               program HEICAP.FOR             *
************************************************

*       This program creates an array of the temperature nodes at the centre of each element
*       for various time intervals.

*       Input file:-    ENGEN.DAT
*                       THERMRES.DAT
*                       EJPDC.DAT

*       Output file:-   TIMETEMP.DAT

*       To change the elemental size the value of L must be altered.
*       The start and stop dimensions must also be correct.


        INTEGER*4       LQ,Q,I,J,K,N,M,NI,NF,MI,MF,E,TT,DT,TM
        REAL*4          R(16,62,2),G(16,62),MC(16,62),T(16,62,2),L,COLP,MEW,TAM,TIM
        CHARACTER       DUMMY*48


        OPEN(UNIT=30,NAME='[SC.RWELLIOTT.SESS86] THERMRES.DAT',TYPE='OLD')
        OPEN(UNIT=31,NAME='[SC.RWELLIOTT.SESS86] ENGEN.DAT',TYPE='OLD')
        OPEN(UNIT=32,NAME='[SC.RWELLIOTT.SESS86] EJPDC.DAT',TYPE='OLD')
        OPEN(UNIT=33,NAME='[SC.RWELLIOTT.SESS86] TIMETEMP.DAT',TYPE='NEW')

        L=0.005                                 !Elemental size in metres.
        TAM=20.0                                !Temperature ambient.
        E=900                                   !Insolation W/m^2

        IF(L.EQ.0.005) THEN
                MI=1                                    !Initial value of M (horizontal)
                NI=2                                    !Initial value of N (vertical)
                MF=16                                   !Final   value of M (horizontal)
                NF=62                                   !Final   value of N (vertical)
        ELSE
                MI=1                                    !Initial value of M (horizontal)
                NI=2                                    !Initial value of N (vertical)
                MF=8                                    !Final   value of M (horizontal)
                NF=32                                   !Final   value of N (vertical)
        ENDIF

*********************************
*       read input files        *
*********************************


*****************************************
*       READ THERMAL RESISTANCES FILE   *
*****************************************

        DO 10 K=1,2
        READ(30,1000) DUMMY
*       WRITE(33,1000) DUMMY
        DO 20 J=NF,1,-1
        IF(L.EQ.0.005) THEN
                READ(30,2001) (R(I,J,K),I=1,MF)         !Thermal resistances.
*               WRITE(33,2001) (R(I,J,K),I=1,MF)                !Thermal resistances.

        ELSE
```

```
                READ(30,2000) (R(I,J,K),I=1,MF)        !Thermal resistances.
*               WRITE(33,2000) (R(I,J,K),I=1,MF)              !Thermal resistances.
        ENDIF
20      CONTINUE
10      CONTINUE

********************************
*       READ THERMAL MASS FILE  *
********************************
*       WRITE(33,2010)
        DO 50 J=NF,NI,-1
                READ(32,2001) (MC(I,J),I=1,MF)         !Thermal mass.
*               WRITE(33,2001) (MC(I,J),I=1,MF)        !Thermal mass.
50      CONTINUE


****************************************
*       READ:- ENERGY GENERATION FILE  *
****************************************

        DO 40 J=NF,NI,-1
        IF(L.EQ.0.005) THEN
                IF (J.GE.(INT((NF+4.1)/2))) THEN
                        READ(31,2001) (G(I,J),I=1,MF)          !Energy generation.

                ELSE
                        DO 46 I=1,MF
                        G(I,J)=0
46                      CONTINUE
                ENDIF
        ELSE
                IF (J.GE.(INT((NF+4.1)/2))) THEN
                        READ(31,2000) (G(I,J),I=1,MF)
                ELSE
                        DO 45 I=1,MF
                        G(I,J)=0
45                      CONTINUE
                ENDIF
        ENDIF

40      CONTINUE

************************************************
*       LOOP FOR DIFFERENT HEAT LOSSES         *
************************************************

        DO 500 H=0,100,25

        J=INT((NF+2.1)/2)
        IF(L.EQ.0.005) THEN
                READ(31,2001) (G(I,J),I=1,MF)
        ELSE
                READ(31,2000) (G(I,J),I=1,MF)
        ENDIF
        READ(31,1) LQ,COLP,MEW

500     continue
        Q=LQ-270

        WRITE(33,2020)
        DO 60 J=NF,NI,-1
        WRITE(33,2001) (G(I,J),I=1,MF)
60      CONTINUE

****************************************
*       INITIALIZE TEMPERATURE ARRAYS  *
```

```
*****************************************

      DO 11 M=1,MF
      DO 22 N=1,NF
      T(M,N,1)=TAM
22    CONTINUE
11    CONTINUE

*************************************************
*     File the temperature matrix [T]           *
*************************************************

      WRITE(33,10000) Q
      WRITE(33,20000) E
      WRITE(33,30000) MEW
      WRITE(33,40000) TAM
      WRITE(33,50000) TT*0.5

      DO 66 N=NF,NI,-1
      WRITE(33,60000) (T(M,N,1),M=MI,MF)
66    CONTINUE

*************************************************
*     LOOP FOR TIME TAKEN EVERY 30 MINS         *
*************************************************

      DO 300 TT=1,24                     !12 hours.
      DT=1                    !DT 0.01sec
      DO 400 TM=DT,180000,DT  !Report temperature distribution every 30 mins.


*************************************************
*     Create NEW temperature array              *
*************************************************

      DO 100 M=MI,MF                     !Horizontal
      DO 200 N=NI,NF                     !Vertical

      IF((M-1).GE.MI) THEN                        !Symmetrical dQ/dx=0
            T(M,N,2)=T(M,N,2)+(T(M-1,N,1)-T(M,N,1))/R(M-1,N,1)
      ENDIF

      IF ((M+1).LE.MF) THEN                       !Symmetrical dQ/dx=0
            T(M,N,2)=T(M,N,2)+(T(M+1,N,1)-T(M,N,1))/R(M,N,1)
      ENDIF

      IF ((N-1).GE.NI) THEN                       !Insulation with ambient.
            T(M,N,2)=T(M,N,2)+(T(M,N-1,1)-T(M,N,1))/R(M,N-1,2)
      ELSE
            T(M,N,2)=T(M,N,2)+(TAM-T(M,N,1))/R(M,N-1,2)
      ENDIF

      IF ((N+1).LE.NF) THEN
            T(M,N,2)=T(M,N,2)+(T(M,N+1,1)-T(M,N,1))/R(M,N,2)
      ELSE
            T(M,N,2)=T(M,N,2)+(TAM-T(M,N,1))/R(M,N,2)
      ENDIF

            T(M,N,2)=(T(M,N,2)+L**2*G(M,N)*E)*DT*0.01/MC(M,N)        !dt 0.01sec
*     type*,tm,m,n,t(m,n,2)
200   CONTINUE
100   CONTINUE


*********************************
*     INITIALIZE ARRAYS         *
```

```
*********************************

       DO 44 M=MI,MF
       DO 55 N=NI,NF
       T(M,N,1)=T(M,N,1)+T(M,N,2)
       T(M,N,2)=0
55     CONTINUE
44     CONTINUE

400    CONTINUE


************************************************
*      File the temperature matrices [T]       *
************************************************

       WRITE(33,10000) Q
       WRITE(33,20000) E
       WRITE(33,30000) MEW
       WRITE(33,40000) TAM
       TIM=TT*0.5
       WRITE(33,50000) TIM

       DO 77 N=NF,NI,-1
       WRITE(33,60000) (T(M,N,1),M=MI,MF)
77     CONTINUE


300    CONTINUE
*500   CONTINUE

1      FORMAT(5X,I3,5X,F5.2,5X,F5.2)
1000   FORMAT(5X,A48)
2000   FORMAT(5X,8F14.10)
2001   FORMAT(2X,17F8.4)
2010   FORMAT(5X,'THERMAL MASS DISTRIBUTION.')
2020   FORMAT(5X,'ENERGY GENERATION FILE')
4000   FORMAT(F12.5)
5000   FORMAT(F5.2)

10000  FORMAT(5X,'The angle of incident radiation is ',I3,' degrees')
20000  FORMAT(5X,'With insolation of 'I4,'  W/m².')
30000  FORMAT(5X,'The efficiency of the collector is ',F5.2,'%')
40000  FORMAT(5X,'The ambient temperature is ',F5.2)
50000  FORMAT(5X,'After ',F5.2,' Hrs the temperature distribution is:-')
60000  FORMAT(2X,16F8.2)


       END
```

```
>L.
   10 REM PROGRAM "SOL"
   20X%=OPENOUT"RES7"
   30?&FE62=&FF
   40CLS
   50INPUT TAB(2,2)"Time in hr= ";HR
   60INPUT TAB(20,2)"Time in min= ";MI
   70MI=MI+60*HR
   80PRINT£X%,MI
   90CLS
  100INPUT TAB(2,8)"Approx flow in ml/s= ";FL
  110PRINT TAB(2,10)"Power should be";FL*4.18*10;"W"
  120?&FE60=0
  130N=ADVAL(3)
  140?&FE60=1
  150P=ADVAL(3)*N*4.92E-7
  160PRINT TAB(2,12)"Actual power= ";P;"W"
  170PRINT TAB(2,14)"When power is correct type C"
  180X$=INKEY$(20)
  190IF X$="C" THEN GOTO 200 ELSE GOTO 120
  200K=20
  210CLS
  22  IM A1(3) : DIM A2(3) : DIM A3(3)
  230DIM AT12(20) : DIM AT23(20) : DIM AT2(20) : DIM AT4(20) : DIM AI(20) : DIM
AP(20) : DIM ATI(20)
  240TIME=0
  250R=0
  260PRINT TAB(1,2)"T12     T23    T2     T4     INT    POW "
  270T12=0 : T23=0 : T2=0 : T4=0 : I=0 : P=0
  280R=R+1
  290FOR M=1 TO K
  300FOR N=0 TO 3
  310TM=TIME
  320?&FE60=N
  330REPEAT : UNTIL TIME>90+TM
  340A1(N)=ADVAL(1)
  350A2(N)=ADVAL(2)
  360A3(N)=ADVAL(3)
  370REPEAT : UNTIL TIME>100+TM
  380NEXT
  390T12=T12+(A1(1)+A1(3))*3.30/(A3(3)*K)
  40  23=T23+(A1(0)+A1(2))*3.30/(A3(3)*K)
  410T2=T2+(A2(0)+A2(2))*20.70/(A3(3)*K)
  420T4=T4+(A2(1)+A2(3))*20.70/(A3(3)*K)
  430I=I+A3(2)*2.13E-2/K
  440P=P+A3(1)*A3(0)*4.92E-7/K
  450NEXT
  460@%=&20205
  470PRINTT12;" ";T23;" ";T2;" ";T4;
  480@%=&20105
  490PRINT" ";I;" ";P
  510AT12(R)=T12 : AT23(R)=T23 : AT2(R)=T2 : AT4(R)=T4 :  AI(R)=I : AP(R)=P : AT
I(R)=TIME/6000
  520IF R<20 THEN GOTO 270
  530FOR R=0 TO 20
  540PRINT£X%,ATI(R),AT12(R),AT23(R),AT2(R),AT4(R),AI(R),AP(R)
  550NEXT
  560GOTO250
```

APPENDIX D

```
>L.
    5 REM PROGRAM RESOUT
    6 PRINT "DATA FILE RES8"
   10X%=OPENIN"RES8"
   20INPUT£X%,TI
   30REPEAT
   40INPUT£X%,ATI,AT12,AT23,AT2,AT4,AI,AP
   50@%=&020003
   60PRINT ATI;" ";
   65@%=&020205
   70PRINT AT12;" ";AT23;" ";AT2;" ";AT4;" ";
   75@%=&020105
   80PRINT AI" ";AP
   90UNTIL EOF£(X%)
```

```
>RUN
DATA FILE RESB
 0.   0.00  0.00  0.00  0.00   0.0  0.0
 1.   3.25 15.55 17.99  6.45   0.0 47.8
 3.   4.71 15.55 19.38  6.47   0.0 45.4
 4.   5.78 15.22 20.52  6.51   0.0 45.2
 5.   6.43 11.92 21.50  6.50   0.0 45.7
 7.   6.64  8.76 22.35  6.55   0.0 42.9
 8.   6.64  6.73 22.96  6.54   0.0 43.1
10.   6.82  5.28 23.60  6.56   0.0 43.6
11.   7.32  4.13 24.19  6.56   0.0 42.2
12.   7.84  3.28 24.74  6.55   0.0 42.3
14.   8.35  2.65 25.25  6.58   0.0 42.0
15.   8.81  2.16 25.69  6.59   0.0 41.8
16.   9.21  1.89 26.08  6.56   0.0 41.9
18.   9.54  1.75 26.41  6.57   0.0 41.9
19.   9.78  1.61 26.65  6.56   0.0 42.2
20.   9.99  1.57 26.89  6.55   0.0 42.0
22.  10.18  1.54 27.09  6.52   0.0 41.9
23.  10.33  1.61 27.24  6.54   0.0 41.8
25.  10.41  1.68 27.35  6.60   0.0 42.7
26.  10.52  1.71 27.54  6.58   0.0 43.5
27.  10.65  1.79 27.71  6.60   0.0 43.5
 0.   0.00  0.00  0.00  0.00   0.0  0.0
29.  10.65  1.94 27.82  6.66   0.0 43.4
30.  10.73  2.03 27.86  6.63   0.0 43.5
31.  10.85  2.09 27.98  6.64   0.0 43.5
33.  10.97  2.11 28.08  6.70   0.0 43.3
34.  11.07  2.14 28.18  6.70   0.0 43.3
36.  11.18  2.14 28.28  6.71   0.0 43.2
37.  11.23  2.21 28.30  6.71   0.0 43.4
38.  11.27  2.25 28.34  6.76   0.0 43.3
40.  11.33  2.27 28.42  6.77   0.0 43.1
41.  11.35  2.29 28.44  6.76   0.0 43.4
42.  11.35  2.31 28.46  6.79   0.0 43.4
44.  11.38  2.34 28.47  6.72   0.0 43.3
45.  11.41  2.36 28.51  6.71   0.0 43.4
47.  11.40  2.39 28.51  6.67   0.0 43.3
48.  11.39  2.42 28.48  6.66   0.0 43.3
49.  11.40  2.46 28.50  6.65   0.0 43.4
51.  11.41  2.48 28.51  6.67   0.0 43.4
52.  11.40  2.48 28.51  6.64   0.0 43.7
53.  11.42  2.47 28.52  6.63   0.0 43.6
55.  11.39  2.47 28.53  6.65   0.0 43.5
 0.   0.00  0.00  0.00  0.00   0.0  0.0
56.  11.35  2.52 28.51  6.65   0.0 42.9
57.  11.15  2.67 28.34  6.66   0.0 43.2
59.  11.12  2.66 28.32  6.64   0.0 42.6
60.  11.12  2.62 28.33  6.64   0.0 42.7
62.  11.15  2.58 28.35  6.63   0.0 42.6
63.  11.16  2.57 28.37  6.63   0.0 42.8
64.  11.20  2.53 28.37  6.60   0.0 43.0
66.  11.25  2.48 28.40  6.58   0.0 43.0
67.  11.27  2.45 28.42  6.55   0.0 43.1
68.  11.14  2.51 28.34  6.52   0.0 43.1
70.  11.08  2.49 28.30  6.50   0.0 43.1
71.  11.13  2.43 28.29  6.50   0.0 43.0
73.  11.16  2.37 28.36  6.48   0.0 42.9
74.  11.16  2.34 28.32  6.45   0.0 42.8
75.  11.13  2.33 28.28  6.42   0.0 43.1
77.  11.10  2.32 28.29  6.42   0.0 42.7
78.  11.09  2.29 28.28  6.43   0.0 42.8
79.  11.01  2.33 28.25  6.42   0.0 42.9
81.  10.98  2.38 28.14  6.42   0.0 43.0
```

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	[illegible]
82.	10.93	2.33	28.16	6.41	0.0	42.8
0.	0.00	0.00	0.00	0.00	0.0	0.0
83.	11.00	2.26	28.21	6.36	0.0	42.8
85.	11.04	2.20	28.24	6.35	0.0	42.7
86.	11.08	2.15	28.27	6.31	0.0	42.6
88.	11.10	2.13	28.28	6.26	0.0	42.8
89.	11.09	2.12	28.24	6.22	0.0	42.7
90.	11.09	2.09	28.25	6.24	0.0	42.4
92.	11.06	2.08	28.21	6.24	0.0	42.6
93.	11.03	2.07	28.23	6.22	0.0	42.9
94.	11.04	2.02	28.22	6.28	0.0	42.9
96.	11.03	1.98	28.22	6.23	0.0	42.9
97.	10.97	1.97	28.23	6.27	0.0	42.7
99.	10.93	1.98	28.19	6.25	0.0	42.4
100.	10.94	1.97	28.20	6.29	0.0	42.5
101.	10.98	1.92	28.23	6.24	0.0	42.5
103.	10.97	1.90	28.21	6.30	0.0	42.4
104.	10.96	1.87	28.22	6.27	0.0	42.3
105.	10.96	1.84	28.22	6.31	0.0	42.6
107.	10.97	1.82	28.23	6.23	0.0	42.4
108.	11.04	1.79	28.23	6.17	0.0	42.4
109.	11.12	1.75	28.26	6.11	0.0	42.5
0.	0.00	0.00	0.00	0.00	0.0	0.0
111.	11.14	1.71	28.28	6.01	0.0	42.5
112.	11.10	1.72	28.25	5.95	0.0	42.7
114.	11.09	1.70	28.26	5.91	0.0	42.5
115.	11.06	1.68	28.25	5.90	0.0	42.6
116.	11.05	1.66	28.26	5.88	0.0	42.8
118.	11.04	1.64	28.25	5.86	0.0	42.7
119.	11.03	1.63	28.25	5.85	0.0	42.8
120.	11.04	1.60	28.27	5.83	0.0	42.9
122.	11.11	1.57	28.32	5.77	0.0	43.1
123.	11.17	1.54	28.31	5.67	0.0	43.0
125.	11.19	1.54	28.31	5.65	0.0	42.8
126.	11.15	1.58	28.23	5.61	0.0	43.0
127.	11.15	1.56	28.24	5.59	0.0	43.3
129.	11.18	1.52	28.27	5.58	0.0	43.0
130.	11.19	1.52	28.27	5.58	0.0	42.8
131.	11.15	1.53	28.25	5.59	0.0	42.8
133.	11.11	1.55	28.23	5.52	0.0	42.6
134.	11.14	1.55	28.16	5.44	0.0	43.0
135.	11.16	1.56	28.16	5.40	0.0	43.0
137.	11.13	1.56	28.25	5.36	0.0	43.1
0.	0.00	0.00	0.00	0.00	0.0	0.0
138.	11.12	1.53	28.14	5.35	0.0	43.0
140.	11.12	1.51	28.17	5.32	0.0	42.9
141.	11.10	1.49	28.19	5.25	0.0	42.7
142.	11.07	1.48	28.17	5.20	0.0	42.4
144.	11.02	1.49	28.14	5.15	0.0	42.4
145.	10.99	1.50	28.11	5.13	0.0	42.6
146.	11.01	1.47	28.12	5.11	0.0	42.5
148.	11.02	1.44	28.12	5.15	0.0	42.7
149.	11.07	1.41	28.13	5.17	0.0	42.8
151.	11.07	1.40	28.13	5.10	0.0	42.9
152.	11.07	1.39	28.14	5.07	0.0	42.8
153.	11.09	1.36	28.13	5.07	0.0	43.0
155.	11.12	1.33	28.15	5.02	0.0	43.0
156.	11.14	1.29	28.16	4.98	0.0	43.0
157.	11.17	1.26	28.15	4.95	0.0	42.9
159.	11.20	1.23	28.18	4.95	0.0	42.9
160.	11.17	1.24	28.15	4.90	0.0	42.8
161.	11.13	1.25	28.11	4.91	0.0	42.6
163.	11.09	1.26	28.10	4.88	0.0	42.9
164.	11.13	1.24	28.11	4.83	0.0	42.7
0.	0.00	0.00	0.00	0.00	0.0	0.0
166.	11.08	1.24	28.08	4.82	0.0	42.7

[illegible]	11.07	[illegible]	[illegible]	[illegible]	0.0	[illegible]
167.	11.06	1.23	28.10	4.78	0.0	42.9
168.	11.09	1.20	28.11	4.84	0.0	42.8
170.	11.09	1.21	28.11	4.87	0.0	42.7
171.	11.03	1.24	28.06	4.92	0.0	43.0
172.	11.05	1.23	28.07	4.91	0.0	42.8
174.	11.05	1.20	28.07	4.85	0.0	42.9
175.	11.06	1.19	28.09	4.83	0.0	43.0
177.	11.03	1.20	28.05	4.85	0.0	43.0
178.	11.08	1.15	28.07	4.83	0.0	43.0
179.	11.14	1.09	28.11	4.75	0.0	42.7
181.	11.16	1.10	28.09	4.70	0.0	42.9
182.	11.16	1.10	28.09	4.67	0.0	42.9
183.	11.15	1.10	28.08	4.65	0.0	42.7
185.	11.09	1.13	28.02	4.60	0.0	42.9
186.	11.07	1.13	28.03	4.58	0.0	42.8
187.	11.04	1.14	28.01	4.55	0.0	42.9
189.	11.02	1.17	27.98	4.65	0.0	43.0
190.	10.97	1.17	27.99	4.78	0.0	42.9
192.	10.92	1.17	27.94	4.74	0.0	43.0
0.	0.00	0.00	0.00	0.00	0.0	0.0
193.	10.88	1.16	27.97	4.66	0.0	43.0
194.	10.90	1.13	27.96	4.64	0.0	43.0
196.	10.96	1.10	27.98	4.63	0.0	43.1
197.	11.02	1.07	28.00	4.65	0.0	42.9
198.	11.05	1.05	28.01	4.69	0.0	42.9
200.	11.05	1.00	28.01	4.66	0.0	43.1
201.	11.06	0.94	28.06	4.59	0.0	43.0
203.	11.08	0.92	28.04	4.56	0.0	42.9
204.	11.10	0.91	28.04	4.49	0.0	42.8
205.	11.07	0.91	28.03	4.47	0.0	42.8
207.	10.97	0.94	28.00	4.46	0.0	43.0
208.	10.92	0.96	27.98	4.45	0.0	43.1
209.	10.90	0.98	27.95	4.47	0.0	42.8
211.	10.93	0.95	27.97	4.46	0.0	43.0
212.	10.96	0.92	28.02	4.55	0.0	43.0
213.	10.93	0.91	28.00	4.52	0.0	43.0
215.	10.92	0.89	28.01	4.55	0.0	42.8
216.	10.98	0.86	28.03	4.49	0.0	42.7
218.	11.04	0.83	28.03	4.48	0.0	42.8
219.	11.06	0.79	28.07	4.52	0.0	43.1
0.	0.00	0.00	0.00	0.00	0.0	0.0
220.	11.07	0.74	28.10	4.52	0.0	43.1
222.	11.11	0.71	28.10	4.50	0.0	43.1
223.	11.13	0.70	28.11	4.46	0.0	42.7
224.	11.12	0.71	28.09	4.45	0.0	42.6
226.	11.08	0.72	28.09	4.44	0.0	42.7
227.	11.10	0.72	28.08	4.46	0.0	42.7
229.	11.12	0.71	28.11	4.48	0.0	42.6
230.	11.12	0.72	28.09	4.46	0.0	42.5
231.	11.09	0.75	28.06	4.44	0.0	42.8
233.	11.11	0.72	28.10	4.43	0.0	43.0
234.	11.16	0.69	28.15	4.48	0.0	43.2
235.	11.20	0.66	28.17	4.43	0.0	43.1
237.	11.13	0.69	28.12	4.50	0.0	43.0
238.	11.12	0.69	28.10	4.43	0.0	43.0
239.	11.06	0.73	28.07	4.40	0.0	43.1
241.	10.99	0.74	28.05	4.39	0.0	43.2
242.	11.03	0.71	28.07	4.45	0.0	43.4
244.	11.11	0.66	28.13	4.45	0.0	43.2
245.	11.12	0.64	28.15	4.42	0.0	43.2
246.	11.15	0.62	28.16	4.43	0.0	43.3
0.	0.00	0.00	0.00	0.00	0.0	0.0
248.	11.18	0.60	28.16	4.40	0.0	43.2
249.	11.20	0.59	28.17	4.39	0.0	43.2
250.	11.17	0.60	28.15	4.36	0.0	43.1
252.	11.15	0.60	28.14	4.40	0.0	43.1

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
253.	11.16	0.58	28.14	4.36	0.0	43.1
255.	11.19	0.56	28.16	4.36	0.0	43.0
256.	11.21	0.54	28.18	4.35	0.0	42.8
257.	11.28	0.51	28.21	4.32	0.0	43.0
259.	11.32	0.49	28.24	4.32	0.0	43.0
260.	11.36	0.48	28.25	4.33	0.0	43.0
261.	11.37	0.48	28.25	4.31	0.0	43.1
263.	11.33	0.51	28.21	4.32	0.0	43.1
264.	11.23	0.58	28.16	4.29	0.0	43.2
265.	11.15	0.61	28.10	4.25	0.0	43.0
267.	11.14	0.63	28.08	4.19	0.0	42.8
268.	11.14	0.65	28.06	4.26	0.0	42.8
270.	11.17	0.63	28.08	4.29	0.0	42.8
271.	11.18	0.62	28.09	4.40	0.0	42.9
272.	11.15	0.60	28.12	4.41	0.0	42.9
274.	11.14	0.53	28.13	4.41	0.0	43.1
0.	0.00	0.00	0.00	0.00	0.0	0.0
275.	11.20	0.52	28.16	4.37	0.0	42.8
276.	11.25	0.48	28.19	4.37	0.0	43.0
278.	11.25	0.46	28.19	4.35	0.0	43.3
279.	11.23	0.44	28.19	4.31	0.0	43.3
281.	11.27	0.39	28.22	4.33	0.0	43.3
282.	11.30	0.35	28.24	4.45	0.0	43.2
283.	11.32	0.32	28.28	4.59	0.0	43.3
285.	11.33	0.29	28.31	4.49	0.0	43.5
286.	11.38	0.27	28.36	4.45	0.0	43.7
287.	11.41	0.27	28.33	4.44	0.0	43.6
289.	11.42	0.24	28.35	4.50	0.0	43.7
290.	11.45	0.21	28.41	4.55	0.0	43.7
291.	11.46	0.19	28.43	4.56	0.2	43.8
293.	11.47	0.19	28.45	4.61	0.4	43.6
294.	11.46	0.19	28.45	4.62	0.6	43.5
296.	11.47	0.22	28.44	4.59	0.7	43.4
297.	11.48	0.24	28.46	4.57	0.7	43.5
298.	11.50	0.24	28.49	4.49	1.1	43.6
300.	11.50	0.23	28.46	4.47	1.3	43.7
301.	11.47	0.25	28.47	4.46	1.9	43.8
0.	0.00	0.00	0.00	0.00	0.0	0.0
302.	11.48	0.26	28.44	4.43	2.3	43.7
304.	11.51	0.27	28.45	4.44	2.6	43.7
305.	11.50	0.29	28.46	4.50	3.1	43.8
307.	11.50	0.29	28.46	4.51	3.7	43.6
308.	11.51	0.30	28.46	4.57	4.2	43.6
309.	11.49	0.30	28.45	4.52	4.6	43.6
311.	11.41	0.33	28.43	4.50	5.5	43.6
312.	11.36	0.37	28.39	4.48	6.0	43.4
313.	11.33	0.39	28.34	4.49	6.6	43.5
315.	11.35	0.40	28.35	4.46	7.3	43.5
316.	11.39	0.39	28.39	4.46	7.7	43.6
317.	11.42	0.37	28.40	4.50	8.4	43.3
319.	11.42	0.37	28.40	4.49	9.4	43.8
320.	11.43	0.35	28.41	4.52	10.5	43.9
322.	11.46	0.32	28.45	4.51	10.9	43.9
323.	11.48	0.29	28.46	4.47	11.2	43.9
324.	11.53	0.27	28.47	4.49	11.9	43.9
326.	11.46	0.35	28.41	4.47	12.7	43.8
327.	11.28	0.50	28.27	4.46	13.8	43.8
328.	11.15	0.61	28.18	4.44	14.5	43.4
0.	0.00	0.00	0.00	0.00	0.0	0.0
330.	11.11	0.65	28.14	4.41	15.4	43.6
331.	11.06	0.71	28.09	4.40	16.0	43.8
333.	11.09	0.69	28.10	4.41	16.8	43.9
334.	11.15	0.65	28.15	4.45	17.6	43.6
335.	11.16	0.64	28.17	4.45	18.6	43.7
337.	11.25	0.57	28.22	4.49	19.6	43.8
338.	11.26	0.51	28.26	4.41	20.3	44.1

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
339.	11.27	0.44	28.29	4.45	21.5	43.8
341.	11.27	0.40	28.30	4.44	22.2	44.1
342.	11.30	0.36	28.33	4.52	23.2	44.3
343.	11.36	0.30	28.37	4.58	23.7	44.4
345.	11.40	0.26	28.43	4.66	24.4	44.7
346.	11.43	0.23	28.45	4.65	26.4	44.6
348.	11.48	0.21	28.50	4.72	28.9	44.7
349.	11.50	0.20	28.53	4.76	44.7	44.2
350.	11.49	0.21	28.54	4.83	75.3	43.8
352.	11.44	0.24	28.53	4.88	90.2	43.9
353.	11.41	0.26	28.51	4.91	97.3	43.8
354.	11.43	0.30	28.53	5.10	102.9	43.7
356.	11.42	0.36	28.53	5.25	108.3	43.6
0.	0.00	0.00	0.00	0.00	0.0	0.0
357.	11.39	0.45	28.53	5.36	113.4	43.4
359.	11.40	0.55	28.53	5.39	117.5	43.5
360.	11.36	0.64	28.54	5.44	121.9	43.6
361.	11.32	0.72	28.55	5.50	125.8	43.4
363.	11.28	0.83	28.53	5.56	130.5	43.3
364.	11.29	0.91	28.55	5.59	129.5	43.6
365.	11.32	0.97	28.57	5.65	121.0	43.6
367.	11.29	1.06	28.54	5.63	113.5	43.4
368.	11.29	1.12	28.54	5.52	126.1	43.3
370.	11.32	1.21	28.55	5.43	152.2	42.9
371.	11.24	1.25	28.59	5.54	156.7	43.9
372.	11.18	1.22	28.62	5.65	157.3	44.0
374.	11.16	1.19	28.66	5.71	164.8	43.8
375.	11.07	1.27	28.61	5.78	174.7	43.9
376.	11.01	1.34	28.58	5.89	182.8	44.2
378.	11.05	1.33	28.65	5.99	188.5	44.3
379.	11.11	1.30	28.76	6.08	194.6	44.5
380.	11.18	1.27	28.84	6.18	201.3	44.4
382.	11.23	1.28	28.92	6.25	207.5	44.6
383.	11.22	1.35	28.96	6.36	213.3	43.3
0.	0.00	0.00	0.00	0.00	0.0	0.0
385.	11.19	1.47	28.96	6.41	219.7	43.1
386.	11.17	1.60	28.95	6.51	227.9	43.2
387.	11.17	1.71	28.99	6.61	235.2	43.7
389.	11.16	1.78	29.01	6.71	240.3	43.8
390.	11.19	1.86	29.01	6.77	243.6	43.6
391.	11.16	1.95	29.04	6.80	238.8	43.6
393.	11.15	2.04	29.07	6.92	247.0	43.5
394.	11.15	2.13	29.06	6.99	256.0	43.4
396.	11.10	2.21	29.05	7.03	251.5	43.1
397.	11.04	2.32	29.03	7.09	231.1	43.1
398.	11.08	2.37	29.04	7.14	231.6	43.1
400.	11.12	2.40	29.03	7.21	241.8	42.8
401.	11.08	2.47	29.02	7.18	243.2	43.0
402.	11.00	2.57	28.97	7.27	269.6	43.3
404.	11.02	2.60	28.99	7.35	293.1	43.4
405.	11.03	2.67	29.00	7.39	300.8	43.4
406.	10.99	2.76	28.99	7.38	307.5	43.5
408.	10.95	2.83	29.01	7.46	318.0	43.7
409.	10.92	2.91	29.03	7.53	331.1	43.4
411.	10.91	2.98	29.04	7.60	341.6	43.4
0.	0.00	0.00	0.00	0.00	0.0	0.0
412.	10.90	3.05	29.05	7.66	352.7	43.5
413.	10.87	3.16	29.07	7.73	363.1	43.5
415.	10.72	3.33	29.01	7.88	375.5	43.2
416.	10.69	3.43	29.01	8.02	386.0	43.0
417.	10.70	3.51	29.03	8.17	397.6	43.1
419.	10.72	3.58	29.06	8.28	407.4	43.1
420.	10.76	3.61	29.08	8.40	415.3	43.1
422.	10.78	3.65	29.18	8.51	422.4	43.4
423.	10.81	3.70	29.27	8.64	429.0	43.5
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
426.	10.78	3.83	29.37	8.83	441.2	43.2
427.	10.77	3.89	29.40	9.05	449.6	43.1
428.	10.77	4.01	29.42	9.21	457.2	42.7
430.	10.75	4.11	29.42	9.34	462.3	42.6
431.	10.76	4.19	29.44	9.59	464.4	42.8
432.	10.77	4.25	29.48	9.79	466.6	42.8
434.	10.80	4.31	29.51	9.82	466.5	42.6
435.	10.84	4.37	29.54	9.91	463.6	42.0
437.	10.82	4.48	29.50	9.84	466.5	41.9
438.	10.77	4.59	29.48	9.92	470.0	42.0
0.	0.00	0.00	0.00	0.00	0.0	0.0
439.	10.68	4.73	29.47	10.12	473.2	42.3
441.	10.63	4.84	29.45	10.27	475.1	42.4
442.	10.62	4.92	29.47	10.40	478.7	42.3
443.	10.62	4.99	29.50	10.57	482.2	42.5
445.	10.62	5.05	29.53	10.64	486.2	42.3
446.	10.60	5.13	29.56	10.76	489.5	42.4
448.	10.58	5.19	29.59	10.86	494.9	42.5
449.	10.58	5.26	29.62	10.96	498.0	42.8
450.	10.59	5.29	29.67	11.09	501.1	42.6
452.	10.61	5.32	29.72	11.18	508.6	42.8
453.	10.62	5.36	29.76	11.36	514.1	42.8
454.	10.61	5.42	29.81	11.54	520.3	42.8
456.	10.60	5.49	29.86	11.65	524.9	42.7
457.	10.62	5.55	29.91	11.67	530.5	42.5
459.	10.65	5.60	29.94	11.80	536.0	42.4
460.	10.62	5.70	29.93	11.93	538.7	42.4
461.	10.60	5.77	29.96	11.99	540.8	42.4
463.	10.59	5.84	30.00	12.00	544.0	42.2
464.	10.57	5.93	30.05	12.08	551.1	42.3
465.	10.54	6.04	30.07	12.26	555.4	42.5
0.	0.00	0.00	0.00	0.00	0.0	0.0
467.	10.52	6.14	30.08	12.36	558.6	42.4
468.	10.49	6.21	30.12	12.49	565.1	42.1
469.	10.48	6.30	30.16	12.52	571.6	41.9
471.	10.47	6.39	30.18	12.72	576.6	41.8
472.	10.48	6.46	30.23	12.81	583.4	41.9
474.	10.46	6.63	30.28	12.90	587.6	42.0
475.	10.43	6.75	30.28	12.85	591.9	42.1
476.	10.41	6.83	30.29	13.00	596.5	42.0
478.	10.44	6.87	30.35	13.08	601.6	42.3
479.	10.43	6.92	30.41	13.17	606.9	42.3
480.	10.42	6.99	30.44	13.08	613.2	42.3
482.	10.43	7.04	30.47	13.25	619.5	42.1
483.	10.42	7.12	30.51	13.28	607.5	42.0
485.	10.32	7.22	30.50	13.31	602.7	42.0
486.	10.24	7.29	30.48	13.31	608.8	40.5
487.	10.15	7.40	30.42	13.38	605.0	37.5
489.	9.98	7.59	30.37	13.19	619.3	42.3
490.	10.10	7.57	30.48	13.29	623.5	43.1
491.	10.19	7.56	30.60	13.30	623.5	43.0
493.	10.19	7.59	30.67	13.42	628.4	43.0
0.	0.00	0.00	0.00	0.00	0.0	0.0
494.	10.25	7.60	30.77	13.55	630.5	42.9
496.	10.36	7.59	30.89	13.59	654.1	43.0
497.	10.41	7.60	30.97	13.47	662.0	42.8
498.	10.35	7.66	31.00	13.87	658.9	42.3
500.	10.29	7.71	31.05	14.03	664.2	42.8
501.	10.29	7.76	31.10	13.76	665.8	43.0
502.	10.34	7.81	31.20	13.92	656.2	43.0
504.	10.40	7.83	31.26	13.81	650.5	42.8
505.	10.46	7.87	31.34	13.80	647.9	42.5
506.	10.47	7.92	31.37	14.05	684.2	43.0
508.	10.40	8.02	31.39	14.24	696.5	38.2
509.	10.19	8.34	31.23	14.46	707.5	37.1
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
512.	9.99	8.74	31.20	14.62	715.9	42.4
513.	10.10	8.80	31.29	14.52	716.4	42.2
515.	10.12	8.89	31.38	14.63	721.2	42.1
516.	10.06	9.00	31.44	14.94	725.7	42.4
517.	10.05	9.07	31.53	14.66	733.8	42.1
519.	10.02	9.12	31.60	15.06	737.2	42.4
520.	9.91	9.18	31.68	15.13	740.2	42.5
0.	0.00	0.00	0.00	0.00	0.0	0.0
522.	9.92	9.17	31.76	15.37	743.1	42.3
523.	10.01	9.18	31.86	15.38	743.9	41.9
524.	10.10	9.23	31.91	15.62	747.1	41.9
526.	10.18	9.27	31.99	15.85	757.7	41.9
527.	10.20	9.34	32.07	15.83	750.3	41.7
528.	10.19	9.41	32.11	15.61	760.8	42.0
530.	10.25	9.48	32.17	15.75	757.3	41.9
531.	10.31	9.56	32.21	15.72	776.7	42.2
532.	10.34	9.68	32.27	15.74	777.0	42.4
534.	10.40	9.79	32.28	15.80	783.1	40.4
535.	10.29	10.02	32.20	15.85	782.2	40.6
537.	10.25	10.18	32.21	16.10	791.0	42.8
538.	10.30	10.24	32.29	16.13	808.2	42.8
539.	10.32	10.35	32.33	16.23	819.8	42.8
541.	10.38	10.46	32.38	16.60	828.7	42.5
542.	10.38	10.61	32.37	16.54	839.1	42.2
543.	10.37	10.74	32.39	16.38	817.3	42.1
545.	10.37	10.83	32.42	16.53	705.0	42.6
546.	10.43	10.78	32.40	16.76	669.3	42.5
548.	10.53	10.63	32.43	16.47	685.7	42.3
0.	0.00	0.00	0.00	0.00	0.0	0.0
549.	10.64	10.51	32.42	16.25	680.0	42.3
550.	10.64	10.42	32.39	16.54	728.7	42.5
552.	10.65	10.40	32.43	16.66	770.0	43.0
553.	10.59	10.47	32.38	16.45	780.6	42.7
554.	10.57	10.61	32.35	16.85	799.7	42.5
556.	10.51	10.80	32.32	16.93	817.1	42.1
557.	10.42	11.01	32.30	16.53	842.8	42.1
558.	10.35	11.23	32.31	16.22	844.3	42.5
560.	10.32	11.40	32.36	16.32	843.6	42.9
561.	10.34	11.55	32.40	16.60	850.7	43.1
563.	10.39	11.67	32.46	16.66	851.1	42.9
564.	10.44	11.76	32.51	17.23	847.1	43.2
565.	10.45	11.82	32.57	17.54	843.5	43.1
567.	10.49	11.88	32.56	16.96	866.8	43.2
568.	10.49	11.93	32.58	17.09	868.5	43.4
569.	10.47	11.99	32.64	17.01	747.6	43.6
571.	10.52	11.89	32.65	16.87	551.4	43.4
572.	10.65	11.48	32.63	17.16	225.1	43.4
574.	10.92	10.51	32.60	17.25	218.5	43.4
575.	11.21	9.53	32.60	16.96	245.9	43.5
0.	0.00	0.00	0.00	0.00	0.0	0.0
576.	11.31	8.75	32.57	16.73	792.8	43.3
578.	11.13	8.84	32.51	15.62	900.6	43.1
579.	10.77	9.33	32.44	15.51	880.3	43.1
580.	10.51	9.79	32.46	16.36	901.0	43.2
582.	10.39	10.31	32.47	16.88	905.7	42.8
583.	10.32	10.87	32.42	15.71	926.5	43.1
585.	10.34	11.40	32.49	16.33	951.6	42.7
586.	10.29	11.99	32.54	16.34	957.0	43.0
587.	10.24	12.52	32.58	16.98	960.3	43.4
589.	10.24	12.92	32.57	17.00	970.1	43.5
590.	10.20	13.20	32.57	17.67	970.1	43.4
591.	10.17	13.35	32.57	17.74	979.2	43.2
593.	10.14	13.47	32.62	17.96	990.7	43.1
594.	10.13	13.58	32.69	18.35	1004.9	43.0
595.	10.10	13.72	32.74	18.47	1004.2	42.8
597.	10.07	13.84	32.76	18.33	1023.6	43.0

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
598.	10.07	13.97	32.79	18.87	1049.5	43.0
600.	10.09	14.10	32.85	19.01	1040.4	43.0
601.	10.13	14.20	32.92	16.69	1056.1	43.0
602.	10.16	14.34	33.00	17.44	1063.2	43.1
0.	0.00	0.00	0.00	0.00	0.0	0.0
604.	10.05	14.47	33.04	18.37	1007.7	43.3
605.	10.01	14.45	33.06	17.61	444.4	43.2
606.	10.21	13.60	33.14	18.11	297.5	43.2
608.	10.67	12.31	33.21	17.50	376.1	43.2
609.	10.94	11.25	33.25	16.52	278.6	43.1
611.	11.04	10.18	33.25	16.64	260.3	43.0
612.	11.10	9.17	33.21	16.11	258.1	43.2
613.	11.16	8.24	33.13	16.10	272.2	43.3
615.	11.21	7.45	33.11	14.89	291.3	43.3
616.	11.26	6.86	33.05	14.49	303.7	43.0
617.	11.22	6.53	32.93	14.35	294.3	42.8
619.	11.14	6.33	32.80	14.35	291.4	43.0
620.	11.09	6.19	32.71	14.78	284.6	42.5
621.	10.96	6.16	32.54	14.46	276.5	42.8
623.	10.93	6.09	32.48	15.11	249.4	42.8
624.	10.88	6.02	32.38	15.19	234.7	42.7
626.	10.86	5.94	32.31	15.59	237.2	42.8
627.	10.89	5.82	32.25	15.60	261.9	42.8
628.	10.88	5.74	32.22	15.88	322.5	42.8
630.	10.84	5.77	32.19	16.11	215.6	42.6
0.	0.00	0.00	0.00	0.00	0.0	0.0
631.	10.86	5.66	32.13	15.34	188.0	42.6
632.	10.94	5.47	32.08	15.16	169.9	42.7
634.	11.00	5.28	32.06	14.85	156.7	42.6
635.	11.04	5.10	32.02	14.47	148.1	42.4
637.	11.03	4.95	31.86	14.29	144.4	42.2
638.	10.97	4.84	31.77	14.60	143.2	42.1
639.	10.90	4.72	31.64	14.22	145.6	41.8
641.	10.87	4.60	31.57	14.17	150.7	41.9
642.	10.88	4.49	31.51	14.30	156.6	41.8
643.	10.82	4.45	31.40	14.51	160.9	42.0
645.	10.83	4.39	31.37	14.15	168.9	42.8
646.	10.90	4.33	31.37	13.87	180.7	42.5
648.	10.90	4.34	31.29	13.53	195.8	42.7
649.	10.92	4.35	31.29	13.48	210.0	42.8
650.	10.90	4.40	31.25	13.79	222.8	42.8
652.	10.86	4.48	31.20	13.62	244.3	42.9
653.	10.87	4.58	31.17	14.14	273.4	42.8
654.	10.85	4.75	31.16	14.41	293.5	43.0
656.	10.81	4.96	31.11	14.52	282.6	42.7
657.	10.77	5.15	31.08	14.74	677.2	42.6
0.	0.00	0.00	0.00	0.00	0.0	0.0
658.	10.61	6.03	31.02	15.29	1085.1	42.4
660.	10.09	7.62	31.01	16.09	1081.6	42.3
661.	9.63	9.12	30.97	16.71	1036.5	42.7
663.	9.53	10.33	30.99	17.37	1051.2	42.8
664.	9.57	11.43	31.08	17.79	1035.5	42.6
665.	9.60	12.37	31.23	17.86	997.8	42.8
667.	9.58	13.08	31.35	18.37	979.7	42.6
668.	9.66	13.56	31.49	18.91	955.0	42.6
669.	9.76	13.79	31.61	19.18	974.5	42.5
671.	9.80	13.91	31.72	18.97	1043.2	42.8
672.	9.76	14.04	31.92	18.62	1050.3	42.9
674.	9.70	14.18	32.02	18.26	1072.7	43.2
675.	9.76	14.33	32.18	19.06	1069.0	43.3
676.	9.77	14.42	32.30	19.21	1006.7	43.5
678.	9.81	14.41	32.44	20.12	987.9	43.4
679.	9.93	14.34	32.60	20.36	927.4	43.2
680.	9.99	14.06	32.71	20.50	488.5	43.5
682.	10.27	13.25	32.87	20.37	1070.5	43.8
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
684.	10.54	12.40	33.08	20.56	455.7	44.0
0.	0.00	0.00	0.00	0.00	0.0	0.0
686.	10.91	11.40	33.16	20.53	459.6	44.3
687.	11.13	10.50	33.25	20.17	363.6	44.3
689.	11.21	9.60	33.25	19.43	324.0	44.6
690.	11.26	8.81	33.23	18.80	279.4	44.5
691.	11.33	8.07	33.23	19.27	240.7	44.5
693.	11.37	7.39	33.22	18.90	210.2	44.4
694.	11.38	6.79	33.15	18.27	185.0	44.2
695.	11.39	6.28	33.11	18.43	167.9	44.4
697.	11.41	5.87	33.06	18.21	157.1	44.3
698.	11.42	5.53	32.99	18.00	148.5	44.0
700.	11.41	5.28	32.96	17.48	141.1	43.5
701.	11.34	5.10	32.85	16.37	134.4	43.8
702.	11.36	4.92	32.76	15.55	131.8	43.8
704.	11.35	4.77	32.71	15.96	132.2	43.8
705.	11.30	4.64	32.61	16.31	137.2	43.7
706.	11.27	4.55	32.54	16.16	144.9	43.8
708.	11.26	4.47	32.48	16.05	151.5	43.9
709.	11.24	4.38	32.44	16.30	155.6	43.9
710.	11.22	4.33	32.40	16.15	159.8	44.0
712.	11.22	4.27	32.35	16.24	167.2	44.1
0.	0.00	0.00	0.00	0.00	0.0	0.0
713.	11.23	4.24	32.29	15.91	177.8	44.1
715.	11.24	4.24	32.23	16.04	190.1	43.9
716.	11.20	4.27	32.19	16.47	199.8	43.8
717.	11.17	4.29	32.14	16.55	205.6	43.7
719.	11.20	4.29	32.12	16.58	209.0	43.6
720.	11.18	4.33	32.08	16.66	211.7	43.2
721.	11.18	4.37	32.03	16.90	214.0	43.6
723.	11.21	4.38	32.01	16.71	214.4	43.8
724.	11.18	4.42	31.97	16.78	211.8	43.7
726.	11.17	4.43	31.95	16.12	208.5	43.8
727.	11.19	4.43	31.93	16.36	205.8	43.9
728.	11.24	4.42	31.91	16.67	203.2	43.9
730.	11.27	4.43	31.90	16.68	199.5	44.0
731.	11.28	4.40	31.86	16.73	194.2	43.8
732.	11.25	4.38	31.82	16.37	189.2	43.9
734.	11.18	4.39	31.77	16.41	184.3	43.9
735.	11.15	4.35	31.74	16.06	180.2	44.0
736.	11.16	4.31	31.73	16.53	175.9	44.0
738.	11.17	4.26	31.69	16.56	170.8	43.9
739.	11.17	4.22	31.68	16.52	165.5	43.7
0.	0.00	0.00	0.00	0.00	0.0	0.0
741.	11.16	4.20	31.64	16.15	159.7	43.6
742.	11.14	4.17	31.58	16.34	154.2	43.8
743.	11.14	4.10	31.59	16.42	149.4	44.1
745.	11.16	4.02	31.56	16.29	144.8	44.2
746.	11.18	3.96	31.53	15.85	141.8	44.2
747.	11.18	3.90	31.52	16.01	138.5	44.3
749.	11.22	3.82	31.54	16.07	135.2	44.2
750.	11.26	3.76	31.54	15.93	131.8	44.2
752.	11.31	3.69	31.53	15.80	128.0	44.3
753.	11.35	3.64	31.51	16.00	124.5	43.8
754.	11.33	3.61	31.47	15.89	121.1	43.5
756.	11.27	3.63	31.39	16.07	118.5	43.7
757.	11.25	3.61	31.33	15.82	116.8	43.7
758.	11.24	3.62	31.28	15.72	115.6	43.7
760.	11.21	3.64	31.22	15.78	114.6	43.8
761.	11.03	3.77	31.03	15.76	114.5	43.5
763.	10.91	3.81	30.89	15.88	114.6	42.7
764.	10.87	3.81	30.83	15.75	116.5	42.0
765.	10.81	3.83	30.76	15.66	118.1	42.1
767.	10.79	3.82	30.71	15.81	119.4	42.1
0.	0.00	0.00	0.00	0.00	0.0	0.0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
769.	10.81	3.76	30.70	15.65	116.0	42.7
771.	10.78	3.74	30.60	15.12	114.0	42.3
772.	10.78	3.69	30.62	15.20	111.4	42.4
773.	10.78	3.64	30.61	14.86	108.0	42.5
775.	10.77	3.61	30.58	14.89	104.0	43.0
776.	10.78	3.54	30.57	14.54	99.5	43.1
778.	10.85	3.46	30.59	14.40	95.3	43.2
779.	10.89	3.37	30.64	14.75	90.9	42.9
780.	10.90	3.31	30.60	14.89	87.3	43.0
782.	10.96	3.23	30.63	15.02	84.3	42.9
783.	10.98	3.17	30.61	14.75	81.1	43.2
784.	10.99	3.10	30.59	14.59	78.2	43.2
786.	11.02	3.05	30.60	14.38	75.6	43.0
787.	11.03	3.01	30.59	14.39	73.1	43.2
789.	11.04	2.97	30.57	14.62	71.0	43.1
790.	11.04	2.96	30.56	14.70	69.0	43.2
791.	11.07	2.92	30.54	14.48	67.0	43.1
793.	11.09	2.91	30.52	14.05	65.5	43.1
794.	11.07	2.91	30.48	13.97	64.2	43.1
0.	0.00	0.00	0.00	0.00	0.0	0.0
795.	11.10	2.85	30.48	14.23	63.3	43.4
797.	11.10	2.83	30.49	14.42	63.0	43.5
798.	11.11	2.82	30.46	14.56	63.2	43.5
800.	11.14	2.80	30.44	14.63	63.4	43.4
801.	11.18	2.77	30.42	14.60	63.4	43.4
802.	11.22	2.72	30.43	14.62	64.2	42.9
804.	11.22	2.72	30.40	14.64	64.7	42.5
805.	11.21	2.73	30.36	14.63	65.7	42.9
806.	11.19	2.75	30.33	14.69	67.2	43.2
808.	11.20	2.74	30.31	14.73	69.8	43.4
809.	11.23	2.70	30.32	14.75	73.0	43.3
810.	11.24	2.69	30.32	14.74	76.2	43.5
812.	11.25	2.68	30.31	14.82	79.6	43.5
813.	11.26	2.67	30.31	14.86	82.5	43.4
815.	11.28	2.66	30.31	14.92	85.1	43.4
816.	11.28	2.65	30.30	14.93	87.3	43.4
817.	11.24	2.68	30.27	15.00	88.8	41.9
819.	11.16	2.75	30.19	14.84	88.8	40.8
820.	11.06	2.85	30.07	14.65	87.6	40.6
821.	10.96	2.94	29.97	14.79	85.4	40.4
0.	0.00	0.00	0.00	0.00	0.0	0.0
823.	10.91	3.00	29.94	14.83	83.0	41.3
824.	10.90	3.01	29.91	14.82	81.0	41.6
826.	10.91	3.00	29.88	14.87	78.7	42.5
827.	10.94	2.97	29.88	14.69	76.3	42.5
828.	10.99	2.93	29.89	14.69	74.6	42.5
830.	11.00	2.88	29.88	14.63	73.5	42.6
831.	10.98	2.85	29.86	14.69	73.8	42.9
832.	11.02	2.78	29.89	14.84	75.5	42.5
834.	11.07	2.71	29.88	14.86	78.3	42.8
835.	11.10	2.67	29.88	14.78	81.8	42.9
836.	11.16	2.64	29.89	14.88	86.0	42.8
838.	11.15	2.65	29.86	14.96	91.6	43.2
839.	11.14	2.64	29.85	14.98	96.3	42.5
841.	11.11	2.67	29.84	15.11	100.8	43.1
842.	11.07	2.72	29.82	15.17	105.9	42.4
843.	11.02	2.79	29.77	15.20	109.4	42.7
845.	11.01	2.83	29.75	15.24	110.6	42.4
846.	11.00	2.86	29.75	15.18	109.3	41.9
847.	10.93	2.92	29.69	15.11	107.0	42.7
849.	10.93	2.93	29.70	15.03	106.1	42.2
0.	0.00	0.00	0.00	0.00	0.0	0.0
850.	10.91	2.95	29.70	15.11	106.0	42.5
852.	10.92	2.94	29.71	15.13	106.5	42.6
853.	10.96	2.92	29.73	15.14	107.6	42.4
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
856.	10.95	2.91	29.74	15.25	111.5	42.2
857.	10.95	2.88	29.73	15.20	114.1	42.7
858.	10.93	2.88	29.73	15.18	119.1	42.4
860.	10.91	2.90	29.70	15.23	126.1	42.2
861.	10.89	2.93	29.68	15.25	134.9	42.8
862.	10.89	2.95	29.68	15.19	146.3	42.4
864.	10.86	3.01	29.72	15.31	162.5	42.5
865.	10.84	3.05	29.69	15.34	177.7	43.1
867.	10.81	3.17	29.70	15.60	182.5	42.7
868.	10.78	3.26	29.69	15.55	192.2	42.8
869.	10.79	3.31	29.72	15.77	200.7	43.0
871.	10.76	3.40	29.72	15.95	208.1	41.5
872.	10.69	3.54	29.69	16.09	214.9	41.0
873.	10.64	3.65	29.66	16.33	224.6	41.2
875.	10.58	3.78	29.62	16.39	230.0	41.2
876.	10.56	3.87	29.64	16.52	229.2	41.1
0.	0.00	0.00	0.00	0.00	0.0	0.0
878.	10.56	3.93	29.64	16.51	231.4	41.1
879.	10.53	4.01	29.63	16.53	228.3	40.9
880.	10.55	4.04	29.64	16.53	221.8	41.0
882.	10.58	4.06	29.66	16.68	213.7	40.8
883.	10.60	4.04	29.62	16.49	205.3	41.0
884.	10.63	4.01	29.67	16.75	197.7	40.9
886.	10.64	3.97	29.65	16.79	189.9	40.9
887.	10.64	3.92	29.62	16.74	182.9	41.8
889.	10.68	3.83	29.69	16.77	179.3	42.8
890.	10.76	3.69	29.74	16.51	181.5	43.0
891.	10.84	3.57	29.80	16.51	188.0	42.6
893.	10.88	3.49	29.83	16.54	196.6	42.8
894.	10.91	3.43	29.86	16.44	232.3	42.6
895.	10.91	3.42	29.87	16.54	402.3	41.0
897.	10.77	3.62	29.83	17.20	580.2	42.4
898.	10.56	3.89	29.85	18.03	660.1	43.2
899.	10.38	4.16	29.89	18.49	662.5	43.1
901.	10.35	4.34	29.95	18.76	299.9	43.2
902.	10.51	4.27	30.07	18.86	228.5	43.0
904.	10.78	4.15	30.12	18.73	208.4	41.6
0.	0.00	0.00	0.00	0.00	0.0	0.0
905.	10.90	4.09	30.07	18.76	183.3	43.4
906.	11.01	3.94	30.16	18.42	163.2	42.8
908.	11.05	3.77	30.19	18.43	147.6	42.6
909.	11.07	3.57	30.22	18.27	134.2	42.1
910.	11.09	3.42	30.18	18.04	125.2	41.7
912.	11.12	3.28	30.17	17.91	119.5	43.3
913.	11.19	3.12	30.22	17.67	115.5	43.4
915.	11.24	3.00	30.24	17.60	111.2	42.8
916.	11.26	2.93	30.21	17.43	105.0	42.6
917.	11.23	2.93	30.17	17.19	97.8	41.3
919.	11.19	2.95	30.11	17.06	92.8	42.9
920.	11.21	2.88	30.07	16.88	87.3	42.8
921.	11.21	2.84	30.03	16.90	82.2	42.9
923.	11.18	2.83	30.05	16.69	78.1	42.7
924.	11.13	2.84	30.02	16.52	74.9	41.3
925.	11.08	2.87	29.94	16.43	74.0	43.0
927.	11.08	2.86	29.92	16.28	75.7	41.1
928.	10.99	2.91	29.82	16.24	79.4	40.5
930.	10.90	2.98	29.73	16.25	82.5	40.4
931.	10.83	3.04	29.66	16.08	83.8	39.2
0.	0.00	0.00	0.00	0.00	0.0	0.0
932.	10.74	3.13	29.57	16.00	82.5	39.3
934.	10.66	3.20	29.48	15.96	78.9	41.7
935.	10.66	3.17	29.47	15.88	74.7	42.7
936.	10.75	3.05	29.54	15.87	70.9	43.2
938.	10.87	2.89	29.62	15.76	68.4	43.2
939.	10.95	2.76	29.70	15.79	66.9	43.0
941.	10.98	2.66	29.72	15.77	65.6	41.5

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
942.	10.96	2.61	29.72	15.72	63.7	42.6
943.	10.99	2.52	29.73	15.70	62.9	43.4
945.	11.02	2.42	29.76	15.67	62.0	43.3
946.	11.07	2.34	29.79	15.63	61.2	43.4
947.	11.10	2.29	29.82	15.52	58.3	42.0
949.	11.02	2.35	29.73	15.49	54.9	41.5
950.	10.99	2.38	29.69	15.50	51.1	43.0
951.	11.01	2.35	29.71	15.49	47.6	43.0
953.	11.02	2.31	29.70	15.39	44.9	43.0
954.	11.05	2.28	29.73	15.34	42.4	42.9
956.	11.08	2.24	29.76	15.24	40.2	43.3
957.	11.11	2.20	29.78	15.18	38.0	42.5
958.	11.08	2.20	29.71	15.16	36.1	41.1
0.	0.00	0.00	0.00	0.00	0.0	0.0
960.	11.03	2.22	29.67	15.09	34.0	42.8
961.	11.03	2.19	29.67	15.00	32.1	42.8
962.	11.04	2.16	29.66	14.93	30.6	42.9
964.	11.05	2.12	29.69	14.92	29.4	42.1
965.	11.02	2.13	29.63	14.86	28.4	40.5
967.	10.96	2.17	29.56	14.73	28.2	42.0
968.	10.94	2.16	29.55	14.73	28.4	42.3
969.	10.93	2.14	29.53	14.73	29.1	42.5
971.	10.94	2.13	29.52	14.68	29.9	42.0
972.	10.94	2.12	29.50	14.54	30.1	42.4
973.	10.96	2.10	29.49	14.48	31.4	41.1
975.	10.97	2.10	29.46	14.44	32.8	42.5
976.	10.99	2.07	29.47	14.40	34.6	41.2
978.	10.94	2.09	29.42	14.33	36.6	41.6
979.	10.94	2.08	29.43	14.30	39.5	42.9
980.	10.97	2.04	29.43	14.24	43.2	41.3
982.	10.92	2.10	29.38	14.20	46.8	41.6
983.	10.82	2.19	29.28	14.03	50.3	42.6
984.	10.77	2.22	29.24	14.02	54.1	42.6
986.	10.80	2.20	29.27	14.03	60.8	42.1
0.	0.00	0.00	0.00	0.00	0.0	0.0
987.	10.83	2.20	29.29	14.03	67.1	42.4
988.	10.79	2.24	29.24	14.06	71.6	40.3
990.	10.71	2.33	29.18	14.08	75.2	42.2
991.	10.74	2.32	29.20	13.99	80.0	42.0
993.	10.78	2.30	29.23	13.95	86.3	42.3
994.	10.80	2.30	29.28	13.92	94.8	42.7
995.	10.81	2.29	29.30	13.94	103.1	42.0
997.	10.79	2.33	29.28	13.88	108.7	41.4
998.	10.72	2.41	29.20	13.87	109.2	41.2
999.	10.70	2.45	29.22	13.96	106.3	42.1
1001.	10.70	2.49	29.22	13.96	103.3	41.8
1002.	10.68	2.55	29.17	13.94	101.9	41.4
1004.	10.65	2.61	29.18	13.97	101.1	40.3
1005.	10.58	2.69	29.08	13.99	100.3	41.1
1006.	10.60	2.69	29.16	13.91	100.2	42.0
1008.	10.63	2.66	29.16	13.98	101.0	42.1
1009.	10.65	2.63	29.19	14.04	100.5	41.9
1010.	10.63	2.63	29.22	14.08	98.9	40.8
1012.	10.58	2.65	29.16	14.10	96.5	41.1
1013.	10.56	2.66	29.14	14.17	93.5	41.9
0.	0.00	0.00	0.00	0.00	0.0	0.0
1014.	10.54	2.64	29.05	14.17	91.0	40.6
1016.	10.54	2.62	29.11	14.20	88.3	40.7
1017.	10.54	2.59	29.05	14.23	86.0	39.5
1019.	10.48	2.62	29.02	14.23	84.6	38.8
1020.	10.42	2.66	28.96	14.17	83.7	39.6
1021.	10.41	2.66	28.99	14.22	83.9	40.0
1023.	10.44	2.61	29.03	14.20	85.1	40.1
1024.	10.47	2.58	29.06	14.19	84.3	39.6
1025.	10.44	2.58	29.02	14.27	82.0	38.1
1027.	10.38	2.63	28.95	14.26	79.5	38.5

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1028.	10.35	2.64	28.92	14.23	78.9	39.1
1030.	10.33	2.63	28.90	14.22	80.7	39.6
1031.	10.32	2.62	28.90	14.19	84.2	39.7
1032.	10.34	2.58	28.91	14.14	88.3	41.5
1034.	10.42	2.50	28.99	14.11	91.8	41.7
1035.	10.49	2.43	29.06	14.09	94.1	40.4
1036.	10.48	2.43	29.05	14.05	94.5	39.9
1038.	10.46	2.44	29.02	14.06	95.1	39.8
1039.	10.46	2.43	29.01	14.09	95.3	39.7
1040.	10.44	2.45	28.98	14.02	96.0	39.5

L.

```
   50 REM PROGRAM ANGLES
  100 MODE 128
  200 VDU (5)
  250 *DRIVE 1
  300 DIM PX(2),PY(4,2)
  400 PROCACON
  500 PROCAXES
  600 PLOT 4,0,30
  700 INPUT "DATA FILE  ";Z$
  750 Y%=OPENOUT("FNAME")
  760 PRINT£Y%,Z$
  770 CLOSE£Y%
  800 X%=OPENIN Z$
  900 INPUT£X%,TI
  910 TI=TI-60
  920 REPEAT
  930 INPUT£X%,ATI,AT12,AT23,AT2,AT4,AI,AP
  940 UNTIL TI+ATI>420
  950 TG=TI+ATI
  960 TJ=ATI
 1000 PROCTIM
 1300 PX(2)=100
 1400 PX(1)=100
 1500 PY(1,1)=70:PY(2,1)=70:PY(3,1)=70:PY(4,1)=70
 1700 PROCANGLE:PROCIX:PROCIY:PROCELOSS
 1800 PLOT 4,100,70
 1900 REPEAT
 2000 PX(1)=PX(2)
 2100 INPUT£X%,ATI,AT12,AT23,AT2,AT4,AI,AP
 2200 IF ATI=0 THEN 2100
 2210 PX(2)=(ATI-TJ)*3+100
 2220 REM PROCANGLE
 2230 PROCIX
 2240 PROCIY
 2250 PROCELOSS
 2300 UNTIL EOF£X% OR ATI>TJ+360
 2400 CLOSE £0
 2450 VDU (4)
 2460 *DRIVE 0
 2500 CHAIN"SCDUMP1"
 2700 END
 2800 DEF PROCTIM
 2900 PLOT4,400,950
 3000 @%=&20205
 3100 PRINT"STARTING TIME ="TG/60.0
 3200 ENDPROC
 3300 DEF PROCACON
 3400 NT1=SIN(RAD(22))*SIN(RAD(50))*COS(RAD(35))
 3500 N1=NT1-SIN(RAD(22))*COS(RAD(50))*SIN(RAD(35))*COS(RAD(45))
 3600 C2=COS(RAD(22))*COS(RAD(50))*COS(RAD(35))
 3700 C3=COS(RAD(22))*SIN(RAD(50))*SIN(RAD(35))*COS(RAD(45))
 3800 C4=COS(RAD(22))*SIN(RAD(35))*SIN(RAD(45))
 3900 SZ=SIN(RAD(22))*SIN(RAD(50))
 4000 CZ=COS(RAD(22))*COS(RAD(50))
 4100 ENDPROC
 7600 DEF PROCANGLE
 7700 N2=C2*COS(RAD(((TI+ATI)/60-12)*(-15)))
 7800 N3=C3*COS(RAD(((TI+ATI)/60-12)*(-15)))
 7900 N4=C4*SIN(RAD(((TI+ATI)/60-12)*(-15)))
 8000 AN=DEG(ACS(N1+N2+N3+N4))
 8100 PY(3,2)=70+10*AN
 8200 PLOT 4,PX(1),PY(3,1)
 8300 PLOT 5,PX(2),PY(3,2)
```

```
8400 PY(3,1)=PY(3,2)
8500 ENDPROC
8600 DEF PROCIX
8700 CW=COS(RAD(((TI+ATI)/60-12)*15))
8800 CSEW=COS(RAD(((TI+ATI)/60-9)*15))
8900 CQZ=SZ+CZ*CW
9000 TQZ=TAN(ACS(CQZ))
9100 IX=DEG(ATN(CSEW*TQZ))
9200 PY(1,2)=70+10*ABS(IX-35)
9300 PLOT 4,PX(1),PY(1,1)
9400 PLOT 5,PX(2),PY(1,2)
9500 PY(1,1)=PY(1,2)
9600 ENDPROC
9700 DEF PROCIY
9750 CSEW=COS(RAD(((TI+ATI)/60-9)*15))
9800 SSEW=SIN(RAD(((TI+ATI)/60-9)*15))
9900 CW=COS(RAD(((TI+ATI)/60-12)*15))
10000 CQZ=SZ+CZ*CW
10100 SQZ=SIN(ACS(CQZ))
10110 T1=SQZ*CSEW*SIN(RAD(35))
10120 T2=CQZ*COS(RAD(35))
10130 DEN=T1+T2
10200 IY=DEG(ATN(SSEW*SQZ/DEN))
10300 PY(2,2)=70+10*ABS(IY)
10400 PLOT 4,PX(1),PY(2,1)
10500 PLOT 5,PX(2),PY(2,2)
10600 PY(2,1)=PY(2,2)
10700 ENDPROC
10800 DEF PROCELOSS
10900 SH=0.15*TAN(RAD(ABS(IY)))
11000 PLEFT=(1-2*SH)*100
11100 PY(4,2)=20*PLEFT-1030
11200 PLOT 4,PX(1),PY(4,1)
11300 PLOT 5,PX(2),PY(4,2)
11400 PY(4,1)=PY(4,2)
11500 ENDPROC
11600 DEF PROCAXES
11700 FOR I=1 TO 6
11800 PLOT 4,I*180-80,70
11900 PLOT 1,180,0
12000 PLOT 1,0,-5
12100 PLOT 0,0,-5
12200 @%=2
12300 PRINT I
12400 NEXT I
12500 FOR I=1 TO 9
12600 PLOT 4,100,I*100-30
12700 PLOT1,0,100
12800 PLOT1,-5,0
12900 PLOT 0,-50,0
13000 @%=1
13100 PRINT I*10
13200 NEXT I
13300 PLOT 4,600,30
13400 PRINT"TIME  (Hrs)"
13500 PLOT 4,0,500
13550 PRINT"DEGS"
13600 FOR I=1 TO 9
13605PLOT 4,1180,I*100-30
13610PLOT1,0,100
13615 PLOT1,-5,0
13616 PLOT 0,50,0
13620 @%=1
13625 PRINT (I+1)/2*10+50
13630 NEXT I
13635 PLOT 4,1180,600
```

```
6100 TT12=0
6200 TT23=0
6300 TT2=0
6400 TT4=0
6500 TAI=0
6600 TAP=0
6700 PX(2)=(AVTI-TJ)*3+100
6800 PROCEFFY
6900 PROCDTE
7000 PROCINSOL
7400 ENDPROC
7500 DEF PROCEFFY
7600 PY(1,2)=1000*(AVP*AVT23)/(AVT12*AVI*0.18)+70
7700 PLOT 4,PX(1),PY(1,1)
7800 PLOT 21,PX(2),PY(1,2)
7900 PY(1,1)=PY(1,2)
8000 ENDPROC
8100 DEF PROCDTE
8200 PY(2,2)=4000*((2*AVT2+AVT23)/2-AVT4)/AVI+70
8300 PLOT 4,PX(1),PY(2,1)
8400 PLOT 5,PX(2),PY(2,2)
8500 PY(2,1)=PY(2,2)
8600 ENDPROC
8700 DEF PROCINSOL
9200 PY(3,2)=70+AVI
9300 PLOT 4,PX(1),PY(3,1)
9400 PLOT 5,PX(2),PY(3,2)
9500 PY(3,1)=PY(3,2)
9600 ENDPROC
11700 DEF PROCAXES
11800 FOR I=1 TO 6
11900 PLOT 4,I*180-80,70
12000 PLOT 1,180,0
12100 PLOT 1,0,-5
12200 PLOT 0,0,-5
12300 @%=2
12400 PRINT I
12500 NEXT I
12600 FOR I=1 TO 9
12700 PLOT 4,100,I*100-30
12800 PLOT1,0,100
12900 PLOT1,-5,0
13000 PLOT 0,-50,0
13100 @%=1
13200 PRINT I*10
13300 NEXT I
13400 PLOT 4,600,30
13500 PRINT"TIME  (Hrs)"
13600 PLOT 4,0,700
13700 PRINT "EFFY %"
14200 PLOT 4,0,400
14300 PRINT"WATTS/10"
14400 FOR I=1 TO 9
14500 PLOT 4,1180,I*100-30
14600 PLOT1,0,100
14700 PLOT1,-5,0
14800 PLOT 0,10,0
14900 @%=&20304
15000 PRINT I/40
15100 NEXT I
15200 PLOT 4,1180,600
15300 PRINT"dT/E"
15400 ENDPROC
```

```
>
  50 REM PROGRAM AGAIN
 100 MODE 128
 200 VDU (5)
 250 *DRIVE 1
 300 DIM PX(2),PY(6,2)
 500 PROCAXES
 600 PLOT 4,0,30
 700 Y%=OPENIN ("FNAME")
 750 INPUT£Y%,Z$
 760 CLOSE£Y%
 800 X%=OPENIN Z$
 900 INPUT£X%,TI
 910 TI=TI-60
 920 REPEAT
 930 INPUT£X%,ATI,AT12,AT23,AT2,AT4,AI,AP
 940 UNTIL TI+ATI>420
 950 TG=TI+ATI
 960 TJ=ATI
1000 PROCTIM
1100 C=0
1200 AVTI=0
1300 PX(2)=100
1400 PX(1)=100
1500 PY(1,1)=70:PY(2,1)=70:PY(3,1)=70:PY(4,1)=70
1700 PLOT 4,100,70
1800 REPEAT
1900 PX(1)=PX(2)
2000 INPUT£X%,ATI,AT12,AT23,AT2,AT4,AI,AP
2050 IF ATI=0 THEN 2000
2100 PROCCOORDS
2200 UNTIL EOF£X% OR ATI>TJ+360
2300 CLOSE £0
2350 VDU(4)
2360 *DRIVE 0
2400 CHAIN"SCDUMP3"
2600 END
2700 DEF PROCTIM
2800 PLOT4,400,950
2900 @%=&20205
3000 PRINT"STARTING TIME ="TG/60.0
3100 ENDPROC
3900 DEF PROCCOORDS
4000 IF AT12=0 OR AI=0 OR AT2=0 THEN 7400
4100 IF C=20 THEN PROCAV
4200 C=C+1
4300 TTI=TTI+ATI
4400 TT12=TT12+AT12
4500 TT23=TT23+AT23
4600 TT2=TT2+AT2
4700 TT4=TT4+AT4
4800 TAI= TAI+AI
4900 TAP=TAP+AP
5000 ENDPROC
5100 DEF PROCAV
5200 AVTI=TTI/C
5300 AVT12=TT12/C
5400 AVT23=TT23/C
5500 AVT2=TT2/C
5600 AVT4=TT4/C
5700 AVI=TAI/C
5800 AVP=TAP/C
5900 C=0
6000 TTI=0
```

```
6300 TT2=0
6400 TT4=0
6500 TAI=0
6600 TAP=0
6700 PX(2)=(AVTI-TJ)*3+100
6800 PROCINSOL
7100 PROCTAV
7200 PROCGAIN
7300 PROCT2
7400 ENDPROC
7500 DEF PROCINSOL
7600 PY(1,2)=AVI+70
7700 PLOT 4,PX(1),PY(1,1)
7800 PLOT 5,PX(2),PY(1,2)
7900 PY(1,1)=PY(1,2)
8000 ENDPROC
9700 DEF PROCTAV
9800 PY(4,2)=10*(2*AVT2+AVT23)/2+70
9900 PLOT 4,PX(1),PY(4,1)
10000 PLOT 21,PX(2),PY(4,2)
10100 PY(4,1)=PY(4,2)
10200 ENDPROC
10300 DEF PROCGAIN
10400 PY(2,2)=10*(AVP*AVT23/AVT12)+70
10500 PLOT 4,PX(1),PY(2,1)
10600 PLOT 21,PX(2),PY(2,2)
10700 PY(2,1)=PY(2,2)
10800 ENDPROC
10900 DEF PROCT2
11000 PY(3,2)=10*AVT2+70
11100 PLOT 4,PX(1),PY(3,1)
11200 PLOT 5,PX(2),PY(3,2)
11300 PY(3,1)=PY(3,2)
11400 ENDPROC
11700 DEF PROCAXES
11800 FOR I=1 TO 6
11900 PLOT 4,I*180-80,70
12000 PLOT 1,180,0
12100 PLOT 1,0,-5
12200 PLOT 0,0,-5
12300 @%=2
12400 PRINT I
12500 NEXT I
12600 FOR I=1 TO 9
12700 PLOT 4,100,I*100-30
12800 PLOT1,0,100
12900 PLOT1,-5,0
13000 PLOT 0,-50,0
13100 @%=1
13200 PRINT I*10
13300 NEXT I
13400 PLOT 4,600,30
13500 PRINT"TIME  (Hrs)"
13800 PLOT 4,0,600
13900 PRINT"TEMP C"
14400 FOR I=1 TO 9
14500 PLOT 4,1180,I*100-30
14600 PLOT1,0,100
14700 PLOT1,-5,0
14800 PLOT 0,50,0
14900 @%=1
15000 PRINT I*10
15100 NEXT I
15200 PLOT 4,1180,600
15300PRINT"WATTS"
15400 ENDPROC
```

```
L.
   50 REM PROGRAM T2T4
  100 MODE 128
  200 VDU (5)
  250 *DRIVE 1
  300 DIM PX(2),PY(2,2)
  500 PROCAXES
  600 PLOT 4,0,30
  700 INPUT "DATA FILE  ";Z$
  750 Y%=OPENOUT("FNAME")
  760 PRINT£Y%,Z$
  770 CLOSE£Y%
  800 X%=OPENIN Z$
  900 INPUT£X%,TI
  910 TI=TI-60
  920 REPEAT
  930 INPUT£X%,ATI,AT12,AT23,AT2,AT4,AI,AP
  940 UNTIL ATI>100
  950 TG=TI+ATI
  960 TJ=ATI
 1000 PROCTIM
 1300 PX(2)=100
 1400 PX(1)=100
 1500 PY(1,1)=70:PY(2,1)=70
 1700 PROCT2:PROCT4
 1800 PLOT 4,100,70
 1900 REPEAT
 2000 PX(1)=PX(2)
 2100 INPUT£X%,ATI,AT12,AT23,AT2,AT4,AI,AP
 2200 IF AT23=0 THEN 2100
 2210 PX(2)=(ATI-TJ)*3+100
 2230 PROCT2
 2240 PROCT4
 2300 UNTIL EOF£X% OR ATI>TJ+360
 2400 CLOSE £0
 2450 VDU (4)
 2460 *DRIVE 0
 2500 CHAIN"SCDUMPT"
 2700 END
 2800 DEF PROCTIM
 2900 PLOT4,400,950
 3000 @%=&20205
 3100 PRINT"STARTING TIME ="TG/60.0
 3200 ENDPROC
 8600 DEF PROCT2
 9200 PY(1,2)=100*AT2-930
 9300 PLOT 4,PX(1),PY(1,1)
 9400 PLOT 5,PX(2),PY(1,2)
 9500 PY(1,1)=PY(1,2)
 9600 ENDPROC
 9700 DEF PROCT4
10300 PY(2,2)=100*AT4-930
10400 PLOT 4,PX(1),PY(2,1)
10500 PLOT 5,PX(2),PY(2,2)
10600 PY(2,1)=PY(2,2)
10700 ENDPROC
11600 DEF PROCAXES
11700 FOR I=1 TO 6
11800 PLOT 4,I*180-80,70
11900 PLOT 1,180,0
```

```
12000 PLOT 1,0,-5
12100 PLOT 0,0,-5
12200 @%=2
12300 PRINT I
12400 NEXT I
12500 FOR I=1 TO 9
12600 PLOT 4,100,I*100-30
12700 PLOT1,0,100
12800 PLOT1,-5,0
12900 PLOT 0,-50,0
13000 @%=1
13100 PRINT I+10
13200 NEXT I
13300 PLOT 4,600,30
13400 PRINT"TIME  (Hrs)"
13500 PLOT 4,0,500
13550 PRINT"TEMP C"
13700 ENDPROC
>
```

```
L.
   50 REM PROGRAM T23
  100 MODE 128
  200 VDU (5)
  250 *DRIVE 1
  300 DIM PX(2),PY(1,2)
  500 PROCAXES
  600 PLOT 4,0,30
  750 Y%=OPENIN("FNAME")
  760 INPUT£Y%,Z$
  770 CLOSE£Y%
  800 X%=OPENIN Z$
  900 INPUT£X%,TI
  910 TI=TI-60
  920 REPEAT
  930 INPUT£X%,ATI,AT12,AT23,AT2,AT4,AI,AP
  940 UNTIL ATI>100
  950 TG=TI+ATI
  960 TJ=ATI
 1000 PROCTIM
 1300 PX(2)=100
 1400 PX(1)=100
 1500 PY(1,1)=70
 1700 PROCT23
 1800 PLOT 4,100,70
 1900 REPEAT
 2000 PX(1)=PX(2)
 2100 INPUT£X%,ATI,AT12,AT23,AT2,AT4,AI,AP
 2200 IF AT23=0 THEN 2100
 2210 PX(2)=(ATI-TJ)*3+100
 2230 PROCT23
 2300 UNTIL EOF£X% OR ATI>TJ+360
 2400 CLOSE £0
 2450 VDU (4)
 2460 *DRIVE 0
 2500 CHAIN"SCDMPT2"
 2700 END
 2800 DEF PROCTIM
 2900 PLOT4,400,950
 3000 @%=&20205
 3100 PRINT"STARTING TIME ="TG/60.0
 3200 ENDPROC
 8600 DEF PROCT23
 9200 PY(1,2)=100*AT23+70
 9300 PLOT 4,PX(1),PY(1,1)
 9400 PLOT 5,PX(2),PY(1,2)
 9500 PY(1,1)=PY(1,2)
 9600 ENDPROC
11600 DEF PROCAXES
11700 FOR I=1 TO 6
11800 PLOT 4,I*180-80,70
11900 PLOT 1,180,0
12000 PLOT 1,0,-5
12100 PLOT 0,0,-5
12200 @%=2
12300 PRINT I
12400 NEXT I
12500 FOR I=1 TO 9
12600 PLOT 4,100,I*100-30
12700 PLOT1,0,100
```

```
12800 PLOT1,-5,0
12900 PLOT 0,-50,0
13000 @%=1
13100 PRINT I
13200 NEXT I
13300 PLOT 4,600,30
13400 PRINT"TIME  (Hrs)"
13500 PLOT 4,0,500
13550 PRINT"TEMP C"
13700 ENDPROC
>
```

```
L.
   50 REM PROGRAM LOG10(T23)
   60 K=0
  100 MODE 128
  200 VDU (5)
  250 *DRIVE 1
  300 DIM PX(2),PY(1,2)
  500 PROCAXES
  600 PLOT 4,0,30
  750 Y%=OPENIN("FNAME")
  760 INPUT£Y%,Z$
  770 CLOSE£Y%
  800 X%=OPENIN Z$
  900 INPUT£X%,TI
  910 TI=TI-60
  920 REPEAT
  930 INPUT£X%,ATI,AT12,AT23,AT2,AT4,AI,AP
  940 UNTIL ATI>100
  950 TG=TI+ATI
  960 TJ=ATI
 1000 PROCTIM
 1300 PX(2)=100
 1400 PX(1)=100
 1500 PY(1,1)=70
 1700 PROCT23
 1800 PLOT 4,100,70
 1900 REPEAT
 2000 PX(1)=PX(2)
 2100 INPUT£X%,ATI,AT12,AT23,AT2,AT4,AI,AP
 2200 IF AT23=0 THEN 2100
 2205 IF AT23<0 THEN 2400
 2210 PX(2)=(ATI-TJ)*3+100
 2230 PROCLT23
 2300 UNTIL EOF£X% OR ATI>TJ+360
 2400 CLOSE £0
 2450 VDU (4)
 2460 *DRIVE 0
 2500 CHAIN"SCDMPT3"
 2700 END
 2800 DEF PROCTIM
 2900 PLOT4,400,950
 3000 @%=&20205
 3100 PRINT"STARTING TIME ="TG/60.0
 3200 ENDPROC
 8600 DEF PROCT23
 9200 PY(1,2)=100*AT23+70
 9300 PLOT 4,PX(1),PY(1,1)
 9400 PLOT 5,PX(2),PY(1,2)
 9500 PY(1,1)=PY(1,2)
 9600 ENDPROC
 9700 DEF PROCLT23
 9800 PY(1,2)=1000*LOG(AT23)+70
 9900 PLOT 4,PX(1),PY(1,1)
10000 PLOT 5,PX(2),PY(1,2)
10100 PY(1,1)=PY(1,2)
10200 ENDPROC
11600 DEF PROCAXES
11700 FOR I=1 TO 6
11800 PLOT 4,I*180-80,70
11900 PLOT 1,180,0
```

```
12000 PLOT 1,0,-5
12100 PLOT 0,0,-5
12200 @%=2
12300 PRINT I
12400 NEXT I
12500 FOR I=1 TO 9
12600 PLOT 4,100,I*100-30
12700 PLOT1,0,100
12800 PLOT1,-5,0
12900 PLOT 0,-50,0
13000 @%=&20103
13100 PRINT 0.1*I
13200 NEXT I
13300 PLOT 4,600,30
13400 PRINT"TIME   (Hrs)"
13500 PLOT 4,0,500
13550 PRINT"LOG(TEMP)"
13700 ENDPROC
>
```